Recommended Procedures to Test the Resistance of Materials to Cavitation Erosion

ABSTRACT
Predicting cavitation erosion under full-scale operating conditions is difficult and relies on laboratory testing using accelerated methods such as ASTM G32-09, Standard Test Method for Cavitation Erosion Using Vibratory Apparatus, and ASTM G134-95, Standard Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet. The main difficulty is that full-scale cavitation intensity is often unknown, and correlating cavitation field characteristics of the accelerated method and the full scale is not obvious. The problem is more acute for compliant polymeric coatings, used for protection or repair of parts subject to cavitation. Extensive testing of such materials shows that, unlike metallic surfaces, they are highly resistant to low-intensity cavitation but fail catastrophically when the intensity exceeds a certain threshold. Such behavior creates the risk of accepting a candidate coating for its resistance to cavitation if the coating was tested at a low cavitation intensity not representative of the application field conditions. This highlights the need to conduct tests with a range of cavitation intensities rather than a single intensity. This article uses results from extensive tests under various forms of cavitation to propose a generalized definition of cavitation intensity. It then presents data on the response of both metals and polymeric coatings to various levels of accelerated cavitation. A new method to test the coatings at varying cavitation intensities is then presented. Such tests provide maps of material resistance to different levels of cavitation and are helpful to make an informed decision. The tests also show that during cavitation exposure, the coatings are subjected not only to mechanical stress but also to significant heating, which
dynamically modifies their properties during the exposure. Temperature rise in the coating when exposed to cavitation is directly connected to the cavitation intensity to which it is exposed, and this interaction needs to be considered.

**Keywords**
cavitation intensity, erosion, testing, weight loss, heating, coatings

**Introduction**

All waters, unless highly treated and in small volumes in a laboratory environment, contain microbubbles invisible to the naked eye and that play a major role in cavitation and boiling. These bubble nuclei are weak points of the liquid and significantly reduce the tensile strength from thousands of atmospheres [1,2] to only 1 atm [3,4]. When the liquid locally experiences a significant pressure drop (e.g., a drop that reduces the pressure below the liquid vapor pressure), it is due to either high local velocities (e.g., in a pump, propeller, orifice, valve, venturi, submerged jets) or intense acoustic waves (e.g., ultrasonic horns, lithotripters); these nuclei react dynamically and grow explosively (i.e., increase several orders of magnitude in volume), thus becoming visible and emitting distinctive sound. These cavitation bubbles later encounter a pressure increase or a return to the ambient pressure, forcing them to collapse violently, emitting shock waves, or forming high-speed reentrant jets, or any combination thereof, both of which are damaging to nearby boundaries [1,2,5–7].

This dependence of cavitation on the natural bubble nuclei has been widely reported in reference books on cavitation [5–7] but is still often forgotten, and most publications on cavitation describe the phenomenon as the vaporization of the liquid ("creation" of cavities) when the pressure drops below the vapor pressure. However, the distinction is important because cavitation is a stochastic phenomenon where the occurrence of the cavitation event, the emission of sound, and the formation of cavitation pits, are directly related to the nuclei distribution in the liquid. Also, for liquids with very small nuclei, the critical pressure below which cavitation occurs can be much smaller than the vapor pressure, and sometimes even negative (tension). This stochastic nature is illustrated in the following sections by the distribution of the impulsive peak pressures generated in a cavitation field as well as the pits generated by bubble collapse in the early stages of cavitation damage.

When a nucleus moves through the flow field of, say, a propeller or a pump, it encounters a time-varying pressure that is due to the acceleration and deceleration of the fluid particles while moving over the rotating blades. The nucleus will react to this field by either oscillating mildly, if it does not go through a highly fluctuating pressure region, or by growing explosively and imploding violently if the pressure drop and rise are significant (see Fig. 1a). This is accompanied by either small-magnitude fluctuations of emitted pressure waves or by intensive pressure peaks and potential shock wave emissions (see Fig. 1b), denoted hereafter as impulsive cavitation pressures.

When a cavitation bubble grows and collapses near a rigid boundary, it does so while deviating very significantly from a spherical shape. The part of the bubble close to the wall is squeezed and flattened by the wall (see Fig. 2a), while the opposite side, able to move more freely away from and toward the wall, returns toward the bubble center much faster than the rest of the bubble and forms a fast reentrant jet (see Fig. 2b) that can reach a
speed of hundreds of meters per second [8]. Fig. 3 shows a visualization of such reentrant jets using a spark-generated bubble collapsing in a pressure gradient (here gravity) [9–11]. Both the shock waves emitted by the bubble compression and at the moment of jet impact on the opposite side of the bubble (see Fig. 4) and the water hammer load that is due to the impact of the jet on the wall induce local stresses in the material [12–14].
In practice, bubbles do not grow and collapse as isolated entities. To the contrary, a cavitation field is a large collection of cavities of different sizes, and cavitation erosion is most intense when clouds of bubbles operate collectively and in concert to generate pressures at orders of magnitude higher than an isolated bubble [15–19]. Concerning cavitation erosion, these bubble clouds in jets [20] or on a propeller blade [21] generate the high driving pressures necessary to make individual microscopic bubbles that are close to the boundary collapse very violently and generate local impulsive loads, which results in stresses in the material exceeding its yield stress.

The high pressure loading results in high stress waves, which propagate radially from the loading location into the material and may cause deformation and failure when stress limits and strains are reached. A pit (permanent deformation) is formed when the local...
equivalent stresses exceed the material elastic limit, and microfailure occurs when the equivalent stresses exceed the material yield stress, the ultimate strength of the material \cite{22,23}, or both. Before failure, the compressive stresses could stay in the material as residual stresses (see Fig. 5) and could have benefits related to peening and improved fatigue life of the material \cite{24}. The effects are compounded because the loads are repeated.
at high rates. The effect of the rate of repetition on the material damage is important, especially in polymeric material where, because of the capability of these materials to recover and their viscoelastic or viscoplastic properties, these materials could resist the loads very well if the frequency of load repetition is low.

Characterization of the Intensity of Cavitation

In practice, cavitation takes many forms, depending on the equipment or configuration where cavitation is generated. These forms include separated individual traveling bubbles, rotating cavitating filaments in turbulent structures, bubble clouds, large attached partial or sheet cavities, and elongated tip vortex cavitating structures. At first sight, these various forms may appear to be of a very different nature, and cavitation under an ultrasonic horn, on a propeller, or in a valve do not seem to have much in common. Upon further analysis, however, all these forms of cavitation are initiated by the dynamics of the preexisting nuclei, and the erosion they generate on nearby materials is due to the collapse of a large distribution of elementary nuclei-initiated cavities [7].

From a material response standpoint, the excitation of the material is simply due to the pressure field generated by the cavitating flow. Under all forms of cavitation fields, this pressure field appears, from high-resolution measurements, to be a distribution of impulsive loads, such as those illustrated in Fig. 6. Such a signal is characterized by repeated impulsive pressures of various high amplitudes and repetition rates. This is further expanded in the next subsection.

Because of this commonality between all cavitation fields and under recommendations from researchers in the cavitation field, ASTM has agreed on two laboratory-scale standard methods to test materials for their resistance to cavitation [25,26]. These have been practiced and used extensively by the industry over the past few decades. One of the methods, ASTM G32-09, Standard Test Method for Cavitation Erosion Using Vibratory

![Example residual equivalent stresses in the material (Al 7075) following collapse of a bubble of initial radius 50 μm, maximum radius 2 mm, and initial distance from the wall 37.5 mm that was driven to collapse by a 10-MPa pressure wave [22–24].](image)
Apparatus [25], is based on generating cavitation using an ultrasonic technique, while the other, ASTM G134-95, *Standard Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet* [26], is based on a cavitating liquid jet technique. Both techniques are intended to accelerate the cavitation erosion process in order to enable evaluation of the materials in a reasonable laboratory time, and both produce cavitation fields intense enough to generate curves of mass loss versus time over the test duration [27]. In the following sections, these two cavitation fields will be used to discuss the characterization of cavitation field intensity and the resulting cavitation damage.

**CAVITATION IMPULSIVE PRESSURES**

Over the past few years, systematic tests were conducted to characterize cavitation pressures both under a cavitating jet and an ultrasonic horn [28,29]. Parallel tests were also conducted in a hydrodynamic facility [29,30]. In all cases, high-frequency response piezoelectric pressure transducers with a rise time of 1 μs and a resonance frequency of 400 kHz (PCB 101A04; MTS Systems Corporations, Depew, NY) were used. The transducers had an exposed sensitive area of about 3.14 mm² (2-mm diameter) and were positioned in the cavitation region of interest. The measurements consisted of recording the pressure signals relevant to each test condition, as in Fig. 6, and to then analyzing these signals and attempting to find correlations between the results.

The pressure signal in Fig. 6 clearly shows the stochastic nature of the impulsive loads imparted onto the material. The amplitude and spacing of the pressure peaks change continually in time and cover a large range of values. Only pressure amplitudes generating material stresses that exceed the material elastic limit contribute to deformation and cavitation damage. This is represented in the figure by the shaded area, which varies depending on the material subjected to this cavitation field. This actually highlights an important aspect of cavitation/material interaction, which is that for the same cavitation field, different materials will effectively see, from a cavitation erosion perspective, different population of impulsive loads, with the "strongest" materials reacting to the smallest number of impulsive loads. This discussion ignores fatigue effects, which would occur over much longer exposure times, or very low rates of loading where a viscoelastic or viscoplastic material recovers between two successive loadings and is more concerned with relatively short-term damage that is due to dynamic instantaneous loading.

**Fig. 6** Typical pressure signal versus time in a cavitation field. Time is expressed in seconds and the pressures are expressed by the voltage detected by the transducer. For materials subjected to this cavitation field, only the peaks generating material stresses that exceed the material elastic limit would contribute to deformation and cavitation damage.
Representing these loads as histograms reveals a character that is specific to the “intensity” of the particular cavitation field. Fig. 7 shows such a histogram, which plots the number of peaks per unit time, \( N(P_{\text{cav}}) \), which have an amplitude comprised in the band \( P_{\text{cav}} \pm \delta P \). Subsequently, it will be better to show the cumulative number of cavitation impulsive pressures per unit time with amplitudes higher than \( P_{\text{cav}}, N_{\text{impulses}}(P_{\text{cav}}) \). Extensive tests under cavitating jets, ultrasonic horn, and hydrodynamic cavitation fields have shown that each cavitation field can be characterized by a very similar well-defined \( N_{\text{impulses}}(P_{\text{cav}}) \) distribution of cavitation impulsive loads. Each of these distributions identifies how intense the cavitation field is, i.e., the intensity of the cavitation field is directly related to the jet pressure in the case of a cavitation jet, to the amplitude of the horn motion in the case of the ultrasonic device, or to the flow rate of the hydrodynamic loop [9].

To illustrate, Fig. 8 shows, for each value of the amplitude of an impulsive peak pressure, \( P_{\text{cav}} \) as shown on the Y-axis, the total number of cavitation impulsive pressures per unit time, which exceed \( P_{\text{cav}} \) measured for cavitating jets with pump pressures varying from 13.8 up to 48.3 MPa. The highest detected peak heights, which are average pressure detected by the transducer over its sensitive area, vary between 100 and 400 MPa for these

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**FIG. 7**
Example of analysis of the pressure signals in Fig. 6 showing the number of impulsive peaks of a given amplitude. For materials subjected to this cavitation field, only the peaks generating material stresses that exceed the material elastic limit would contribute to deformation and cavitation damage (1,000 psi ≈ 6.9 MPa).

**FIG. 8**
Cumulative number of peaks versus peak amplitude for different pump pressures used to generate the cavitating jets.
pump pressures, and the cumulative number of peaks vary between 10,000 and 50,000 impulsive peaks per second. Increasing the cavitation intensity (i.e., the cavitating jet pressure or velocity) is seen to increase both the number of impulsive pressure peaks and the amplitude of the generated pressure.

Further analysis indicates that each of the $N_{\text{impulses}}(P_{\text{cav}})$ can be represented by an analytical expression of the form:

$$N_{\text{impulses}} = \exp \left[ - \left( \frac{P_{\text{cav}}}{P_{\text{reference}}} \right)^{2.54} \right], \quad N_{\text{impulses}} = \exp \left( -P_{\text{cav}}^{2.54} \right) \quad (1)$$

In this expression, $N_{\text{reference}}$ is an important parameter, which can be used as a reference indicating the characteristic cumulative number of peaks per unit time for the particular cavitation flow field. Similarly, $P_{\text{reference}}$ is another important reference parameter, which is the characteristic impulsive pressure peak height of the particular cavitation flow field. Using these two key parameters to normalize the equation describing each particular distribution leads to a universal curve of $N_{\text{impulses}} = N_{\text{impulses}}/N_{\text{reference}}$ versus $P_{\text{cav}} = P_{\text{cav}}/P_{\text{reference}}$, which is applicable to all measured cavitation fields [7,28]. This is illustrated in Fig. 9, where all curves presented in Fig. 8 are seen to collapse on the same curve when the normalization is applied. The same was found to apply for ultrasonic cavitation and for the hydrodynamic cavitation tests conducted [28,29].

Both $P_{\text{reference}}$ and $N_{\text{reference}}$ parameters are required to characterize the intensity of cavitation of a given setup and were obtained for the investigated cavitation field as follows. Fig. 10a shows variations of these parameters with the pump pressure (i.e., flow velocity) for both the cavitating jets and the hydrodynamic loop. Interestingly, $P_{\text{reference}}$ is seen to vary linearly with the pump pressure and is approximately three times the pump pressure, which makes its evaluation simple. The variations of the characteristic number of impulsive pressure peaks, $N_{\text{reference}}$, with the pump pressure are shown in Fig. 10b for both the cavitating jet and the hydrodynamic cavitation loop. A dependence on the 2.13 power of the pump pressure can be seen. As we will see later, this corresponds to a similar pump power for erosion mass loss progression [30–32].

An additional characteristic of the cavitation impulsive pressures is the duration of these impulsive pressures. This duration, $\Delta T$, is illustrated in Fig. 11 and is defined as the

**FIG. 9**
Normalized plot of cumulative number of peaks versus peak amplitude for different jet pressures, compared with the curve of Eq 1.
**FIG. 10**

Cavitation field intensity characteristics for different cavitation conditions: (a) $P_{\text{reference}}$ versus pump pressure and (b) $N_{\text{reference}}$ versus pump pressure.

**FIG. 11**

Illustration of a cavitation impulsive pressure peak width, $\Delta T$, with peak amplitude, $P$, and number of impulsive peaks per second, $N_{\text{impulses}}$. 
width of the base of the pressure peak when intersected by a line defining the pressure threshold above which cavitation damage may occur, e.g., above the elastic limit of the considered material. Here too, the distribution of peak widths is stochastic but is also indicative of the intensity of the cavitation field. Even though it has not been studied as in depth as the amplitude and the number of peaks, plotting for different cavitation intensities the impulsive pressure width versus the amplitude of the peaks shows a clear trend as illustrated in Fig. 12. As the intensity increases, and here as the pump pressure increases, the amplitude of the peaks increases while the width of the pressure impulse is reduced. Therefore, thinner and higher amplitude impulses are generated as the cavitation intensity increases. The dashed lines in the figure also indicate where the largest numbers of peaks are located in the map scatter plot.

MATERIAL PITTING FROM CAVITATION

The conduction of pitting tests has been suggested for a long time as a substitute for measuring the cavitating flow field impulsive loads [33–35]. Actually, because of the complex fluid structure interaction, there is not a direct one-to-one connection between pressure distribution and pit counts [23,36]. However, pitting data is also stochastic, and there is a good connection between cavitation intensity and pit number and size distributions.

Cavitation pitting tests are conducted in a similar way as cavitation erosion tests. However, one has to be careful to operate during (a) the incubation period, i.e., during the period where the material experiences plastic permanent deformation but without any material loss, and (b) over periods of time short enough to avoid the pits from single cavitation events overlap [33,37–39]. Fig. 13 shows a raw microscopic image of the pits generated on a nickel aluminum bronze (NAB) sample, which was subjected to a 3,000 psi cavitating jet for 1 min. The image clearly shows a large distribution of pits with various shapes and sizes in the region of the jet where cavitation bubble collapse occurred.

Advanced techniques, such as contact profilometers, laser profilometers, optical profilometers, or scanning electron microscopes [40], can be used to analyze these pits. An
An optical profilometer was used to generate the pictures shown in Fig. 14, where the color contours are indicators of the elevation of the surface of the sample, with green being the initial zero elevation [37]. The blue regions indicate the deeper pits, while red indicates areas that have been extruded (note, however, that the zero level is difficult to establish with great accuracy). The figure shows qualitatively that the number of pits and their depth increases with the cavitation intensity, here with the jet pressure.

Detailed analysis of such images enables one to generate histograms of the number of pits with equivalent diameters or depths larger than a selected value, such as presented earlier for the cavitation field pressures (e.g., Fig. 8). Fig. 15 presents an example of such histograms, showing the results of pitting tests on NAB samples with cavitating jets and ultrasonic ASTM G32-09 tests. The figure shows that for each test the cumulative number of pits per unit time and area with equivalent diameter larger than a specific pit diameter. Here again, for a given cavitation test condition (and material) all data falls along a Weibull or exponential function with two characteristic parameters, $N_{p,\text{reference}}$ and $D_{\text{reference}}$:

$$\frac{N_{pits}}{N_{p,\text{reference}}} = \exp\left[-\left(\frac{D_{pits}}{D_{\text{reference}}}\right)^{0.7}\right], \quad N_{pits} = \exp(-D_{pits}^{0.7})$$

(2)
As seen in Fig. 16, when representing the pitting rate versus pit diameter using the normalized quantities $N_{pits}/N_{p,reference}$ and $D_{pit}/D_{reference}$, all histograms for the various materials exposed to various cavitation intensities in a cavitating jet or an ultrasonic horn practically fall on the same curve, $N_{pits} = \exp(-D_{pit}^{0.7})$.

Therefore, the parameters $N_{p,reference}$ and $D_{reference}$ characterize the interaction between a particular cavitating field condition and a particular material. The combination

FIG. 15
Measured pitting rate (or cumulative number of pits per unit time and area with equivalent diameter larger than a specific diameter) on NAB samples from exposure to ultrasonic cavitation and cavitating jets at various cavitation intensities (1,000 psi $\approx$ 6.9 MPa).

FIG. 16
Normalized pitting rate versus normalized equivalent pit diameter for a set of tests on Al 7075, stainless steel A2205, and NAB exposed to cavitating jets and ultrasonic cavitation (1,000 psi $\approx$ 6.9 MPa).
Variation of the pitting characteristic parameters with the pump pressure. Example for stainless steel A2205 and cavitating jets (1,000 psi ≈ 6.9 MPa).

Cavitation Erosion Resistance

While experiments and measurements, such as described in the previous sections, are conducted for research purposes in order to understand the mechanisms involved with cavitation dynamics and material erosion, practical material testing using ASTM G32-09 [25], ASTM G134-95 [26], and similar techniques are conducted regularly and extensively. Such tests are used to practically evaluate material resistance to cavitation, compare the effects of various material treatments, and examine new formulations or the effectiveness of the application of various coatings on the resistance to cavitation. In these evaluation tests, samples of the material with prescribed shapes in the direct methods or of user-selected shape for indirect or substitute methods are subjected to the cavitation generated from a nozzle or an ultrasonic horn [27].

The sample and sample holder are designed or marked in such a way as to ensure that the sample can be returned to the same position after each testing interval. The sample is exposed to the cavitation field for a selected duration and is then removed for evaluation. This involves examining the material, recording high-resolution detail pictures, weighing the sample to determine weight loss, or measuring the volume of the removed material and estimating an average depth of erosion. More sophisticated methods are sometimes used to obtain a 3-D profilometry of the eroded area or a simpler 1-D cross-cut of the erosion profile. From the measurements mentioned previously,
characteristic curves of the evolution of erosion in time are obtained and allow comparison between samples and materials. In order for the test to be meaningful, the time intervals have to be selected appropriately to capture all portions of a cavitation erosion curve that include the following periods: incubation, acceleration, steady state, and deceleration (see Fig. 18).

All cavitating jet results presented in this article used a simple nozzle with a hemispherical convergent section followed by a sharp edge, short, straight section of diameter 0.086 in. (2.2 mm). The nozzle shape is illustrated in Fig. 19.

**CAVITATION EROSION OF METALS**

The pattern of the erosion of a metallic material under the ultrasonic horn is usually quasi uniform but varies significantly between the direct method (sample of special shape directly attached to the horn) (see Fig. 20a) and the alternative method (sample placed in a holder parallel and below the horn tip equipped with a sacrificial sample of a material highly resistant to cavitation) shown in Fig. 20b. Fundamentally, in the direct method the bubble cloud formed under the horn is hemispherical, while in the indirect method the bubble cloud is cylindrical. A spherical bubble collapse being more energetic than a
cylindrical one explains why the indirect method results in a slower and less intense erosive process [41].

The pattern of the erosion produced by a cavitating jet is more dynamic and varies significantly over time with the jet pressure. Initially, most of the erosion is on the periphery of the submerged jet since it is generated by the dynamics of the bubble nuclei captured by the liquid vortices in the shear layer between the high-speed liquid and the host liquid (see Fig. 21a). As material removal advances and the sample surface profile evolves, chunks of material are removed, making the center of the sample deeper and deeper with an irregular shape (see Fig. 21b). One can still recognize the resulting erosion patterns as being due to cavitation because of the granular-like heavily pitted shape of the surface. Note by comparing the erosion times in Figs. 20 and 21 that the ASTM G32-09 method requires a much longer exposure time to cavitation to achieve significant mean depth of erosion even when compared with a jet of only 1,100 psi (7.6 MPa). The cavitating jet in the ASTM G134-95 method or a similar jet method allow evaluation of the most erosion-resistant materials in a much shorter turnover time.

Observation and measurement of cavitation erosion in different facilities and at different levels of cavitation (cavitating jets and hydrodynamic cavitation at a large set of velocities and ultrasonic cavitation ASTM G32-09) of various metals have all shown that the cumulative mass loss, $M$, or the volume loss or mean depth of material removal, $h$, time evolution for different cavitation intensities follow the same functional trend [31,32], such as in the following:

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FIG. 20
Evolution of the cavitation pattern on an Al 7075 sample under an ultrasonic horn: (a) ASTM G32-09 direct method procedure after 300 min and (b) ASTM G32-09 alternative method procedure after 900 min.

FIG. 21
Evolution of the cavitation pattern on an Al 1100 sample under a cavitating jet: (a) 900 psi jet after 60 min and (b) 1,100 psi jet after 220 min (1,000 psi $\approx$ 6.9 MPa).
This is illustrated in Fig. 22, which shows as examples a set of tests conducted on NAB samples using both the cavitating jets and the ultrasonic ASTM G32-09 method. To fit the expression in Eq 3, three parameters, which are all material and cavitation field dependent, need to be known or extracted from the measurements. The first represents a shift in time to bring the time zero point to the beginning of the mass loss using the incubation time, \( t_{\text{inc}} \). This is a known property of the material’s cavitation erosion resistance and is a function of the particular cavitation intensity. The other two parameters are: \( h_{\text{reference}} \), which is a characteristic reference depth, and \( t_{\text{reference}} \), which is a characteristic reference time. Both also depend on the considered material and the “cavitation intensity” (e.g., flow velocity or cavitation number).

Eq 3 can be rewritten using the normalized quantities as follows:

\[
M = M_{\text{reference}} \left( 1 - e^{-\left(\frac{t_{\text{inc}}}{t_{\text{reference}}}\right)^2} \right) + M_{\text{reference}} \frac{1}{e} \left( \frac{t - t_{\text{inc}}}{t_{\text{reference}}} \right)^{1.2}
\]

(3)

\[
h = h_{\text{reference}} \left( 1 - e^{-\left(\frac{t_{\text{inc}}}{t_{\text{reference}}}\right)^2} \right) + h_{\text{reference}} \frac{1}{e} \left( \frac{t - t_{\text{inc}}}{t_{\text{reference}}} \right)^{1.2}
\]

(4)

This expression is written here for the mean depth of erosion, but the same form of the expression also applies to the cavitation erosion mass loss or volume loss [31,32].
A large set of data for NAB, Al 7075, and stainless steel A2205, normalized in this way, is shown in Fig. 23.

CAVITATION EROSION OF POLYMERIC COATINGS

Coatings are increasingly being applied to protect material surfaces in order to delay deterioration of the substrate material and subsequent part replacement. Cavitation erosion studies of coatings have addressed, amongst others, polymers [42], nonmetallic coatings [43], epoxy resins and coating layers [44,45], and ultra-high molecular weight polyethylene [46]. However, cavitation resistance of polymeric coatings is still relatively unknown as testing such materials has three major difficulties when compared to metals:

(a) The comparative “softness” of the coatings leads to a relatively large dynamic response to the imposed cavitation impulsive pressures. This results of strong interaction between the collapsing bubbles and the coating, with the coating interface motion feeding back and modifying the source of the impulsive load, i.e., the dynamics of the collapsing bubble itself. Modeling of these effects are a subject of ongoing efforts (e.g., Refs. [35,47,48]). For instance, Fig. 24 illustrates the level of the interaction between a coating and a cavitating bubble and shows that in a pressure field that is due to a 1,000 psi (6.9 MPa) cavitating jet, the interface deformation can be ∼15 % of the bubble maximum radius, which is significant. In the case of an imposed acoustic field, such as in an ultrasonic device, the dynamic deformations can actually affect and locally modify the acoustic pressure field itself. For this reason, ASTM G32-09 cautions against using the acoustic testing method for polymeric materials [25].

(b) The second major effect of cavitation on polymeric materials is the heating of the material, which is much less important for metals. This was reported, for instance, in Ref. [49] where the temperature rise of plastic specimens subjected to cavitating flows was observed to be an order of magnitude higher than it was for metals. These effects will be discussed in more detail.

(c) The third potential effect that is present with polymeric coatings and is not relevant in metals is the capability of the polymer to recover from deformation because of its viscoelastic or viscoplastic behavior. This property affects the polymeric coating response to a cavitation field excitation when the frequency of repetition of the impulsive loads is smaller than the inverse of the recovery time.
In the following, we will discuss tests and observations conducted with polyurea coatings. Polyurea was investigated because of its reportedly good performance as a reinforcement of metal structures against shocks from blast and impact loads [50]. However, its performance under cavitation loading is compromised by excessive local heating, which significantly modifies its properties and affects its performance [51–53]. Its material properties were characterized under a range of different strains and strain rates in Refs. [54–57]. The material was shown to be very sensitive to strain rate with its properties transitioning from rubbery to glassy as the strain rate increases. The rheological and yield properties of polyurea were also shown to be highly sensitive to temperature with the storage and loss moduli dropping by a factor of about four when the temperature increases from 0°C to 50°C [58]. Results from such local heating can be seen in Fig. 25 on a polyurea-coating sample subjected to a cavitating jet of pressure 800 psi (cavitation at this pressure is very weak for metallic surfaces and would not result in any measurable erosion even after hours of exposure). The coating is seen to behave plastically and to flow out of the formed crater away from the substrate. The full thickness of the coating is pierced in less than a minute. As the material’s local temperature rises, the shear modulus drops significantly, followed by plastic flow and formation of a large crater with extruded material at its rim.

The effects of the temperature on the cavitation erosion resistance of a polyurea coating are well illustrated in the tests presented in Fig. 26, which shows the response of the polyurea coating to cavitation exposure at different temperatures. In all four experiments...
shown in the figure, the polyurea coating and substrate were brought to the indicated temperatures (40°C, 20°C, 5°C, −10°C) and placed rapidly in the test tank. The water temperature was also made to be the same but for the test at −10°C, for which the tank water temperature was kept at 5°C, while the samples was subcooled to −10°C. As observed, under this last condition, the polyurea resistance to cavitation was the largest, and the material did not show any deformation for up to 90 s of exposure to the cavitation generated by an 800-psi jet. This incubation period (here indicating a rather sudden sharp change in behavior that resulted in subsequent fast catastrophic failure) is seen to decrease systematically as the temperature is increased, reaching practically zero when the P650 polyurea was tested at 40°C. Once the incubation period (the time to heat the material to behave in the plastic mode) is exceeded, and the penetration of the cavitating jet through the material occurs very fast over a short time period, during which the maximum depth of penetration was reached in 20 to 50 s.

This makes the evaluation of polymeric coatings difficult, especially because performance is strongly dependent on the thickness of the coating, a fact that is not well characterized. As illustrated in Fig. 27, several tests have shown that a thicker coating results in more excessive heating, produces larger craters, and fails earlier.

**Translating Jet Tests**

As we saw in the previous section, in stationary cavitation testing setups, such as in ASTM G32-09 and in the stationary cavitating jet, cavitation simultaneously heats the polyurea and dynamically stresses it. In order to separate these two effects, a translating jet cavitation test was developed at DYNAFLOW (Jessup, MD) [52,53]. In this new method, the cavitating jet nozzle location and the jet pressure versus time are computer-controlled. The cavitating jet can be translated over the test sample using a selected translation speed, therefore subjecting each location of the sample to cavitation only for a controlled short duration and thus reducing heat accumulation at the same location during the test. Changing the jet pressure as the jet is translated also allows for exposure of the sample during the same test to a range of cavitation intensities. Varying jet pressure range and translation speed on the same test panel provides a wealth of information about the coating resistance to cavitation.

As shown in Fig. 28, the nozzle is mounted on an X-Y translation table powered by two step motors, which enable the user to move the cavitating jet along a selected trajectory. In addition, a metering valve upstream of the nozzle enables control of the cavitating...
jet pressure (cavitation intensity) as the nozzle changes location. In the following test examples, the pressure was varied linearly between two specified values, while the jet was translated at a constant translation speed. The effect of this translation speed was also investigated [51,52].

With this approach, one can easily extract from the cavitation damage pattern (see, for example, Fig. 29) the threshold pressure and the threshold translation speed,
respectively, above which and below which the coating material fails. This is illustrated in the tests shown in Fig. 29 where a 1-mm-thick coating of P1000 polyurea on a 4-in.-long aluminum substrate was subjected to a cavitating jet. The jet was translated at a speed of 0.01 in./s (∼0.25 mm/s) starting from the left end of the panel. As the nozzle moved from left to right, the nozzle inlet pressure was raised in a linear fashion from a starting pressure of 700 psi (∼4.8 MPa) at the left end of the panel to a pressure of 1,100 psi (∼7.6 MPa) at the right end. For a distance of about 1.4 in. (∼3.56 cm), which corresponds to a start pressure of 700 psi (∼4.8 MPa) and an end pressure of ∼840 psi (∼5.79 MPa) (the two repeated tests gave 834 (∼5.75 MPa) and 845 psi (∼5.82 MPa)), the coating sufficiently resisted the cavitating jet effects. Upstream, prior to reaching the threshold pressure, the tests sometimes show a smooth linear permanent shallow dimple left in the material with no material removal. Beyond the threshold position (i.e. above the threshold pressure), the coating is seen to deform and flow further and further plastically as the pressure increases. At the same time, the width and depth of the erosion path increases as the pressure increases. Also, the plasticized material is seen to flow up and re-solidify as extruded parts, as seen in the bottom side view picture in Fig. 29.

The procedure described above can be used to obtain maps of [cavitating jet pressure, translation velocity], which delineate operating parameters resulting in cavitation erosion, versus safe operating regions. Such maps are far more instructive than the results obtained by a stationary jet operated under one fixed pressure condition or by the ultrasonic ASTM G32-09 test. An example of such diagrams, here for three formulations of the polyurea coating, can be seen in Fig. 30. All three formulations are combinations of Isonate 143L, and an Amine: PU-1000 uses VP1000 for the amine, PU-650 uses VP650, and the blend uses a 76:24 weight ratio of a mixture of VP1000 and VP650. Diagrams, such as in Fig. 30, can be further expanded into contour plot by adding the depth of the erosion path at each couple [cavitating jet pressure, translation velocity].

**Measurements of Polyurea Heating**

Heating of the polyurea when subjected to cavitation can actually be measured during the event. This was achieved using K-type thermocouples and a thermocouple-to-analog converter implanted in the polyurea coating at various depths [52, 53]. These measured the time evolution of the coating temperature as the sample was subjected to cavitation. The measurements taken at different depths also provided the distribution of the temperature through the thickness of the material.
Stationary Jet Temperature Increase Tests

Two types of measurements were performed. In the first, a stationary cavitating jet, as described in the ASTM G134-95 method, was used. To avoid damaging the thermocouples, the tests were limited to pressures not exceeding 500 psi (3.45 MPa). With the sample below the jet, the temperature variation with time was very typical and very repeatable. As shown in the five test repeats in Fig. 31, the temperature starts rising rapidly as soon as the cavitating jet is turned on (here at $t = 1$ min). For the 400 psi (2.76 MPa) condition shown in the figure, within 1 min, the temperature rose about 18°F. The temperature increase, $\Delta T$, then saturated at $\sim 20^\circ$F and does not change significantly after that, i.e., here between $t = 3$ min and $t = 6$ min.
In order to investigate the potential for thermal recovery of the polymeric coating after removing the loading, Fig. 32 compares the pressure rise in the polyurea when it is subjected continually to the jet for 5 min versus when the jet is turned on and off every 30 s. It is clear from these tests that while the interruption results overall in less heating, 30 s of an off period of the excitation is not long enough to allow complete recovery of the material from the thermal excitation. This is consistent with the temperature drop curves in Figs. 32 and 33, both indicating the need of at least 2 min for full recovery. This illustrates that for polyurea, the effect of recovery is not too strong for cavitation condition.
resulting in impulsive load repetition frequencies larger than one event per minute. This is a very slow repetition rate compared to all the cavitation configurations we have studied (see, for example, Ref. [59] for cavitation inception, and Fig. 8 and Table 1 in this article).

The maximum value of the temperature increase, $\Delta T_{\text{max}}$, can then be used to characterize the temperature change for various cavitation conditions. For instance, in Fig. 33, we can observe how $\Delta T_{\text{max}}$ at a depth of 1.5 mm in a 2-mm-thick P650 polyurea with poly(methyl methacrylate) substrate, on the cavitating jet axis, $r = 0$, varies with the jet pressure. It is seen to increase from 5°F (28°C) for a jet pressure of 300 psi (2.1 MPa) to 32°F (17.8°C) for a jet pressure of 500 psi. The corresponding increase in the heating effect of the polyurea is quite significant. The figure also shows how the temperature rise is distributed in the radial direction under the cavitating jet. This temperature rise in the polyurea drops significantly (e.g., by a factor of 3 for the 500-psi (3.45-MPa) jet) between the point corresponding to the jet axis and at a radial distance of 0.3 in., i.e., about 16 nozzle radii (the nozzle orifice diameter was 0.04 in.).

The temperature increase also depends to a large extent on the material of the coating substrate. This is because of the capacity of the substrate to act as a heat sink and evacuate the accumulated heat to various degrees depending on its own heat dissipation properties [52,53]. For instance, tests with polyurea on aluminum and poly(methyl methacrylate) substrates have shown large differences in the resulting $\Delta T_{\text{max}}$ with heating being significantly reduced with the aluminum substrate. This is mainly due to the thermal diffusivity of aluminum ($9.7 \times 10^{-5}$ m$^2$/s) being three orders of magnitude larger than that of poly (methyl methacrylate) ($1.1 \times 10^{-7}$ m$^2$/s). This large difference in behavior is illustrated in Fig. 34, which shows the resulting maximum temperature increase with aluminum and poly(methyl methacrylate) substrates at three depths of the temperature measurement ($d = 0.5, 1.0, \text{and} 1.5$ mm). As the temperature gauge is placed deeper in the coating thickness, the $\Delta T_{\text{max}}$ decreases in the case of aluminum (again because of its good diffusivity), forcing the temperature to be maximum near the polyurea water interface. However, for the poly(methyl methacrylate) substrate, which requires more time to evacuate the pressure, the maximum temperature increase is located at midcoating thickness as seen clearly in the figure for the jet pressure of 500 psi (3.45 MPa).

**Translating Jet Temperature Increase Tests**

The translating jet setup, briefly described in the previous section, was also used to measure how the maximum temperature rise in the polyurea, $\Delta T_{\text{max}}$, decreases with the jet translation. To do so, the thermal response of the material with the translating jet was again measured using a thermocouple implanted in the polyurea. This is illustrated in Fig. 35, which clearly shows that, as expected, the amplitude of the measured temperature peak decreases with the jet translation speed, dropping from $\sim 26^\circ$F (14.4°C) for a

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**TABLE 1**

Characteristic amplitude and number of cavitation impulsive pressures in cavitating jets at a set of operating pressures ($1,000$ psi $\approx 6.9$ MPa).

<table>
<thead>
<tr>
<th>Jet Pressure, psi</th>
<th>$P_{\text{reference}}$, psi</th>
<th>$N_{\text{reference}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>6,250</td>
<td>2,415</td>
</tr>
<tr>
<td>4,000</td>
<td>12,500</td>
<td>10,000</td>
</tr>
<tr>
<td>6,000</td>
<td>20,500</td>
<td>18,500</td>
</tr>
<tr>
<td>7,000</td>
<td>21,000</td>
<td>26,500</td>
</tr>
</tbody>
</table>
translation speed of 0.01 in./s to ~12°F (6.7°C) for a translation speed of 0.08 in./s. The various temperature versus distance curves also show that the width of the peak (i.e., the extent of the area where the temperature rises because of the cavitating jet) increases with the translation speed, becoming almost three times larger when the translation speed increases from 0.01 to 0.08 in./s. For the same dynamic reason, the peak temperature is seen to lag behind the jet, i.e., it occurs after and not at the same time as the jet center goes over the thermocouple. This lag also increases significantly with the translation speed.
Testing of Materials Resistance to Cavitation—Discussion

In the material presented in the previous sections, an overview of the various advanced aspects of the physics of cavitation and of the interaction of cavitation with metallic and polymeric materials was presented. In this section some additional discussion is presented addressing practical aspects of the selection of an erosion testing method and procedure.

Commonly used ASTM G32-09 offers a clearly specified procedure with a single set of conditions to test various materials. This has the advantage of reducing ambiguity in the testing and allowing comparison of materials’ resistances using the same exact procedure. However, since the strengths of the various practical materials subjected to cavitation span a very wide range of strength, erosion tests that use ASTM G32-09 can become very lengthy for the most resistant materials and can even be inadequate. The range of cavitation intensities to test a set of selected materials with cavitating jets is shown in Fig. 36, which presents the minimum jet pressure (cavitation intensity) required to observe any cavitation erosion in, say, four hours of testing. For the materials shown in the figure, this jet pressure varies from \( \sim 700 \) to \( \sim 3,000 \) psi, a power range varying by more than an order of magnitude. The figure also shows the recommended testing pressure for each of the materials, indicating a pressure range between \( \sim 800 \) and 7,000 psi; again, a range of powers of almost two orders of magnitude.

To relate this somewhat to the ASTM G32-09 tests, we can examine its cavitation pressure field and compare it to that of a cavitating jet. As described in the “Cavitation Impulsive Pressures” subsection, each cavitation field is characterized by a specific distribution curve of a number of cavitation impulsive pressures that exceed a given pressure amplitude. If, for illustration, we arbitrarily select the amplitude to be \( \sim 60 \) MPa (\( \sim 8,700 \) psi), we can determine which cavitating jet produces the same number of impulses with amplitudes higher than \( \sim 60 \) MPa. Fig. 37, for instance, shows a set of ultrasonic power settings and a set of cavitating jet pressures where the number of impulsive pressures exceeds 60 MPa. From this figure, we can deduce that the ultrasonic device, run at 60 % power setting, produces \( \sim 140 \) pressure impulses per second, which

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**FIG. 36**
Minimum cavitating jet pressure, shown on the X-axis, to obtain weight loss larger than 0.5 mg over 2 h of testing in different materials. The chart also shows recommended pressures to test these materials in an “accelerated” fashion, i.e., obtain erosion curves in less than 4 h (1,000 psi \( \approx \) 6.9 MPa).
is about the same number as a cavitating jet operating at \(\approx 1,050\) psi (7.2 MPa). Actually, this is just to provide an order of magnitude of the jet pressure needed to produce comparable effects. In fact, as repeated often in this article, a whole curve of the number of impulses versus amplitude needs to be matched to produce the same exact effects. For this reason, comparisons between a cavitating jet and an ASTM G32-09 test show correspondence when the cavitating jet is in between 1,000 and 2,000 psi (6.9 and 13.8 Mpa), depending on the materials tested and the criteria used.

Using either the cavitating jet always at 1,000 to 2,000 psi (6.9 to 13.8 MPa) or the ASTM G32-09 is, however, not satisfactory when testing materials for their cavitation resistance. First, as we observed with Fig. 36, this cavitation intensity is too low to obtain results within a reasonable time for cavitation-resistant materials. In addition, one fundamental reason why this is inadequate is that the intensity of cavitation fields in different applications or at various application geometric scales can vary widely. Using an accelerated method to test the material should not only accelerate the erosion, it should use levels of cavitation excitation (impulsive loads) commensurate with the levels encountered in the practical application. Using a lower level is inadequate because it provides a false sense of safety, making the user believe that the material would resist the full-scale operating environment while it may not at all.

As introduced directly in the section on “Cavitation Impulsive Pressures” and indirectly in the section on “Material Pitting from Cavitation” (see, for example, Fig. 15 where ASTM G32-09’s resulting pit number distribution can be compared directly with the cavitating jet pit distribution), various cavitation fields are characterized at a given material location by a specific distribution of number of impulsive pressure peaks per unit time versus the amplitude of these peaks. This distribution is characterized by two independent variables: a characteristic number of impulses and a characteristic amplitude with usually both of them increasing with the intensity of cavitation.

**FIG. 37**

Number of impulsive pressure peak higher than \(\sim 60\) MPa for different cavitating jet pressures and ultrasonic device percent power settings. This illustrates that ASTM G32-09 at a setting of 60 % results in the same number of peaks as the cavitating jet operating at 1,050 psi (1,000 psi \(\approx 6.9\) MPa).
Assume we know the distribution of cavitation impulsive pressures in the practical application that the material to be tested will experience, i.e., the distribution corresponding to the green dashed curve in Fig. 38. In order to perform an accelerated test, i.e., obtain the same results as in the real field test but in a shorter time, we need a cavitation field that corresponds to the dashed orange curve or the red solid curve in Fig. 38, which, respectively, correspond to time acceleration factors 4 and 20. Here, the red curve with the factor of 20 was drawn using the impulsive pressures distribution corresponding to a cavitating jet operating at 4,000 psi. This time acceleration would not be proper if it transforms the cavitation operation condition from one where the frequency \( f_{\text{loads}} \) of the loads is lower than the inverse of the time the material needs to recover through its viscoelastic properties to one at 4 \( f_{\text{loads}} \) or 40 \( f_{\text{loads}} \), which does not allow such a recovery. However, as discussed earlier, for polyurea considered in this study, recovery time is two orders of magnitude longer that the inverse of the lowest repetition rate of the impulsive loads measured in a typical cavitation field, making the time acceleration of no consequence from the material recovery point of view.

Instead, if the material is tested using a cavitation field corresponding to the blue curve in Fig. 38, which for illustration corresponds to a 2,000 psi (13.8 MPa) cavitating jet or approximately an ASTM G32-09 pressure field, a major conceptual error is introduced. With such an approach, while the number of impulsive pressures of amplitudes between \(~10\) and 55 MPa (\(~8,000\) psi) is multiplied by a factor of 4 or less, all much more damaging impulsive pressures above 55 MPa are not well represented. Those between \(~55\) and \(~85\) MPa are underrepresented (i.e., less than in the field application, while all highly damaging impulsive pressures higher than 85 MPa are absent. Such a test will undoubtedly indicate a cavitation erosion resistance that is much better than in reality, especially for materials that have ultimate strengths above \(~70\) MPa, for the example in the figure.

This can be illustrated in a more convincing way by using actual comparative tests between Aluminum Al6061 and a P1000 polyurea coating for the same cavitation source,
i.e., the same cavitating jet. In the tests, the cavitation intensity was varied and the results compared. First, we consider the response to a stationary cavitating jet at 800 psi. As shown in Fig. 39, after 2 h of exposure to this relatively weak cavitating jet, polyurea shows a very strong resistance, with no measurable deformation, indentation, or material loss under the jet. On the contrary, Al6061, which has a yield point of 40,000 psi (~275 MPa), experiences progressive erosion with a small crater under the jet with its depth continually increasing in time and attaining an average depth of 12 μm after the 2 h of exposure. If one stops at this test, the conclusion would clearly be that polyurea P1000 is far superior in cavitation erosion resistance to Al6061, which is a poor sales pitch for the polymeric material. Based on the previous discussion, such a procedure and conclusion would obviously lack thoroughness.

Testing the material at various cavitation intensity levels is now shown in Fig. 40. In this figure, Al6061 results for a cavitating jet at 2,000 psi (13.8 Mpa) are compared with...
erosion progression on polyurea P1000 using three jet pressures: 800, 1,100, and 1,300 psi (5.5, 7.6, and 8.96 MPa). These tests show a typical behavior of polymeric materials. Below a certain threshold, about 900 psi (7.6 or 8.96 MPa), cavitation impulsive pressures are too weak to affect the material and bubble collapse is weakened by the material elastic response [48]. However, above the threshold, e.g., a jet pressure of 1,100 or 1,300 psi as shown in Fig. 40, the polyurea could resist cavitation for no longer than tens of seconds and is thereafter significantly damaged. Based on the observations of temperature increase in the material described in previous sections that are above a given cavitation intensity threshold, heating combines with cavitation dynamics effects, leading to the polyurea failure. This is not the case with the Al6061, which, as seen in the figure, is much more resistant to a 2,000-psi jet by gradually and very slowly losing weight and eroding at a rate of an order of magnitude slower, without failing precipitously as the polyurea.

This illustrates the need to conduct tests at various cavitation intensities in order to acquire an accurate view of the material resistance to cavitation and to compare the performance of various materials.

Summary

In this article, cavitation interaction with various materials and resulting erosion were presented from both fundamental and applied points of view. Cavitation is the result of the explosive growth and violent collapse of microcavities initially present in the liquid as bubble nuclei. The collapse of these cavities generates repeated high levels of impulsive loads, which are characteristic of the phenomenon. Classical descriptions of cavitation fields use the value of cavitation intensity to characterize a given erosive field. Actually, further study shows that cavitation fields generated in a variety of ways can each be characterized by a curve/distribution of impulsive loads, which represent \( N_{impulse} \) the number (per unit time and unit area) of impulsive pressure peaks with an amplitude higher than \( P_{impulse} \). These distributions can all be normalized using the couple \( (P_{reference} \) and \( N_{reference} \) to give a unique relationship between normalized peak numbers and peak amplitudes. As an illustration \( P_{reference} \) and \( N_{reference} \) for a set of cavitating jet pressure is shown in Table 1.

In the early stage of a material erosion by cavitation, the collapse of the bubbles results in the formation of pits on the material’s surface as a result of permanent plastic deformation of the material. These pits are also observed to follow characteristic distributions of the number of pits with diameters exceeding a given value. Once normalized by a reference number of peaks, \( N_{p,reference} \) and a reference pit diameter, \( D_{reference} \), which uniquely characterizes the combination cavitating field and material, all conditions result in the same functional distribution: \( N_{pits} = \exp\left(\frac{-D_{pit}^{0.7}}{D_{reference}}\right) \). This pitting rate distribution correlates with the distribution of cavitation impulsive pressure peaks rate [29].

Cavitation erosion progression (time evolution of mass removal or mean depth of erosion) in metals has also been shown to follow similar functional forms for various cavitation intensities and metals exposed to cavitation. Here also, in addition to the well-known incubation time, \( t_{inc} \), two characteristic parameters of erosion progression have been identified for the combination erosion field and material: \( h_{reference} \) and \( t_{reference} \). Normalizing the mean depth of erosion with \( h_{reference} \) and the difference between time and \( t_{inc} \) by \( t_{reference} \) all erosion progression curves collapse on \( \tilde{h} = 1 - e^{-T} + \frac{1}{2} T^{1.1} \).

Erosion progression on polymeric materials is more complex and more difficult to describe using a unique functional form. This is due to the fact that the properties of a
polymeric coating evolve over time when exposed to cavitation effects, which are due to heat generated by the strain imposed on the material. Significant temperature rise in polyurea has been measured under controlled conditions and this is known to correlate with softening of the material and strong reduction in its yield strength. Because of these interactive effects, a strongly nonlinear behavior is observed with polymeric coatings, which switch suddenly from highly resistant to cavitation to catastrophic failure with a small increase in the cavitation intensity. In order to better evaluate polymeric materials, a translating jet erosion testing method was proposed in this article. This method enables minimization of heating effects and exploration of a range of cavitation intensities on the same test panel.

Finally, a discussion of the procedure to test materials to cavitation erosion was presented. This illustrated the need to examine any new material to be tested for cavitation erosion under various cavitation intensities in order to properly evaluate its resistance to cavitation. This is necessary in view of the fact that quite often, the intensity of the cavitation to which the material will be exposed is unknown. This is the case, for instance, for full-scale propellers or appendages where qualification for cavitation is made using small-scale tests, since full-scale tests are difficult to perform and evaluate.

ACKNOWLEDGMENTS

This article is based on R&D work supported by the Office of Naval Research under contracts N00014-11-C-0378 and N00014-15-C-0052 monitored by Dr. Ki-Han Kim and by internal DYNAFLOW, INC. funds. The author appreciates the contribution of several DYNAFLOW employees, including Dr. Jin-Keun Choi, Pauline Marlin, Arvind Jayaprakash, Sowmitra Singh, and Patrick Aley, to the extensive tests on which this article is based, and thanks Dr. Alireza Amirkhizi from the University of Massachusetts at Lowell and Dr. Jay Oswald from the University of Arizona for useful discussions and Dr. Alireza Amirkhizi for providing polyurea samples.

References


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Materials Performance and Characterization


