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The process (mechanism) of erosion of soluble brittle materials caused by cavitation

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Abstract

This research determines which of the phenomena that appear during cavitation are responsible for the erosion of some brittle water soluble materials, such as gypsum and alum, when exposed to a high intensity ultrasound field over the cavitation level. The observation that gypsum suffers no erosion under the effect of an ultrasound field when the material is irradiated in a saturated solution of gypsum in water initiated the idea of performing this experiment. © 1997 Elsevier Science B.V.

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Cavitation has been a well-known phenomenon for about a century now. The amount of knowledge concerning this phenomenon, which consists of thousands of studies, is summed up in text books [1] and review articles, such as the well-known article by Suslick [2] in *Scientific American*. Thus, one can study the phenomena that are associated with cavity implosion in every detail.

The phenomena are: (1) the creation of hot spots within the liquid where the temperature of the gas in the cavity rises to thousands of degrees Celsius; (2) the formation of high pressure shock waves during the cavity implosion; and (3) cavity implosion generates a powerful liquid jet when the cavity is formed near a solid surface. The implosion is asymmetric, expelling a jet of liquid directed at the surface that moves at speeds of roughly 400 km h^{-1}. When the bubbles do not implode, as happens in the case of stable cavitation, we have oscillation of the bubbles within an equilibrium bubble radius due to the acoustic field. In this case, microstreams are formed around the bubbles. These phenomena, associated with the oscillation and implosion of the bubbles, cause a series of effects, such as the rectified diffusion of gas to the bubble interior. This causes the erosion of solid surfaces, removal of nonreactive coatings and chemical reactions facilitated by high temperatures and pressures inside the bubble or near the surface of the bubble.

The phenomena associated with cavitation occur simultaneously or consecutively, in a short space of time. For this reason we can never be sure which is the main mechanism responsible for the action of ultrasound cavitation in various materials. The following experiments aim at defining the main mechanism responsible for the erosion of gypsum and alum in an ultrasonic field under cavitation conditions.

1. Experimental instruments and results

The transducer used had a 2.54 cm diameter operating at 0.8 MHz. The average intensity of the beam transmitted was 4 W cm^{-2}. Our measurements, which were performed using calorimetric methods as well as those of Loucas and Biquard [3], indicated that the intensity of the beam, at a distance (underwater) of 10 cm from the transducer, was 8 W cm^{-2}, not only in the center of the beam, but also within a radius of 3 mm from it. On the other hand, in the external ring, defined by the area included between a 9 and 12 mm radius, the intensity of the beam decreased to 1.3 W cm^{-2}.

Most experimental samples used were plates made of gypsum and alum whose dimensions were $35 \times 45 \times$ (2 or 5 mm) thickness. The experiments were carried out using pure water and different concentrations of solutions. We used saturated solution of gypsum (100%) and solutions of 25, 50 and 75% saturation. The plates were placed at a distance of 10 cm from the transducer with their largest area perpendicular to the beam. The volume of solutions used was 1000 cm^3. We purposefully

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used a large quantity of water to avoid significant influence on the degree of saturation, from the mass lost from the samples during sonication.

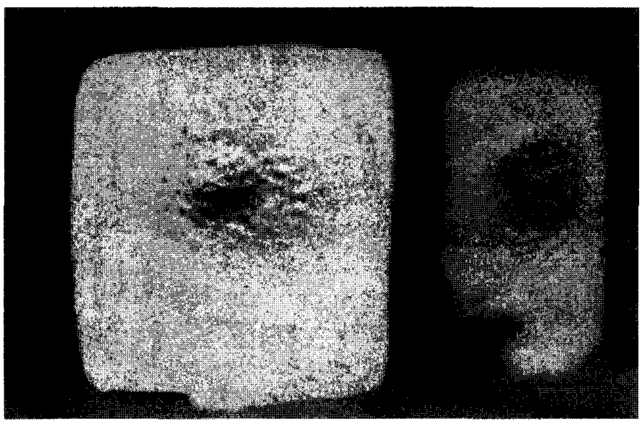
Experimental tests in pure water, lasting 1 h, indicated a profound erosion of gypsum in the center of the beam until about 12 mm diameter (Fig. 1(a)). The effects on alum (Fig. 1(b)) were more intense. So we decided to make tests at a distance of 10 cm from the transducer with the erosion to be tested by weighing the plate before and after the test. Five such tests with gypsum plates were made in solutions with different concentration of gypsum. The solutions were filtered before use to avoid suspension. The results are indicated in Fig. 2.

In pure water and without being irradiated, a pilot plate of the same size lost 30 mg in 10 min. Then we used a stainless steel reflector (width $\lambda/4$; λ = wavelength in steel) in order to create a standing wave and a thin plate (2 mm) of gypsum was placed vertical to the reflector (Fig. 3). It was found out that the erosion of the plate was formed in lines parallel to the reflector. The mean distance between successive lines was 0.914 mm, that is to say $\lambda/2$ of the ultasound wavelength in the water.

In order to find out whether the erosion occurs in the nodes or antinodes of pressure of the standing wave, an experiment was necessary which demanded a great deal of accuracy. For this purpose, we treated the alum on a glass rectangular plate by scraping the sides so that they were precisely flush with the edges of the glass plate. We proceeded by placing the alum plate in the standing wave field, as we previously did with the gypsum plate. Erosion lines were also formed parallel to the reflector at a distance from each other of $\lambda/2$ in the water. Following this, the dried plate of alum was rubbed on carbon paper placed on a plain, smooth surface in order to darken the noneroded areas while the eroded areas remained white.

After magnifying the picture (Fig. 4) we measured the distances between the 22 most intense white lines (the eroded areas) formed on the alum plate from the edge adjacent to the reflector during the irradiation. It was found out that these distances were all even multiples of 0.457 mm which is equal to $\lambda/4$ (λ = the wavelength in water at 23.5°C). We found that the erosion occurred on the nodes of motion (antinodes of pressure) of the standing ultrasound field.

Another experiment (without using ultrasounds) was performed to determine the effects of the erosion on a gypsum plate using a pure water jet and a jet of saturated



a b

Fig. 1. Erosion after 1 hour sonication: (a) gypsum; (b) alum.

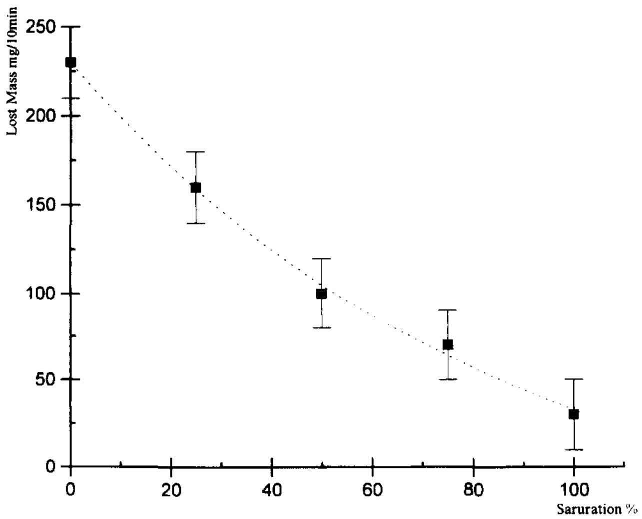


Fig. 2. Mass of gypsum plates lost by ultrasonic erosion as a function of solution saturation.

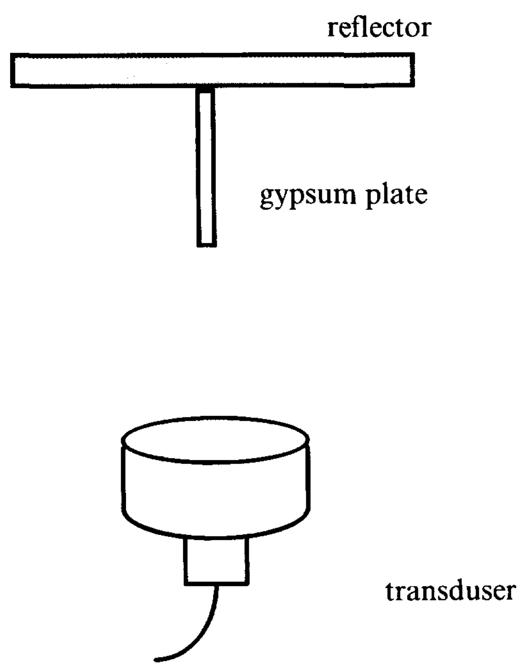


Fig. 3. Erosion under stading wave.

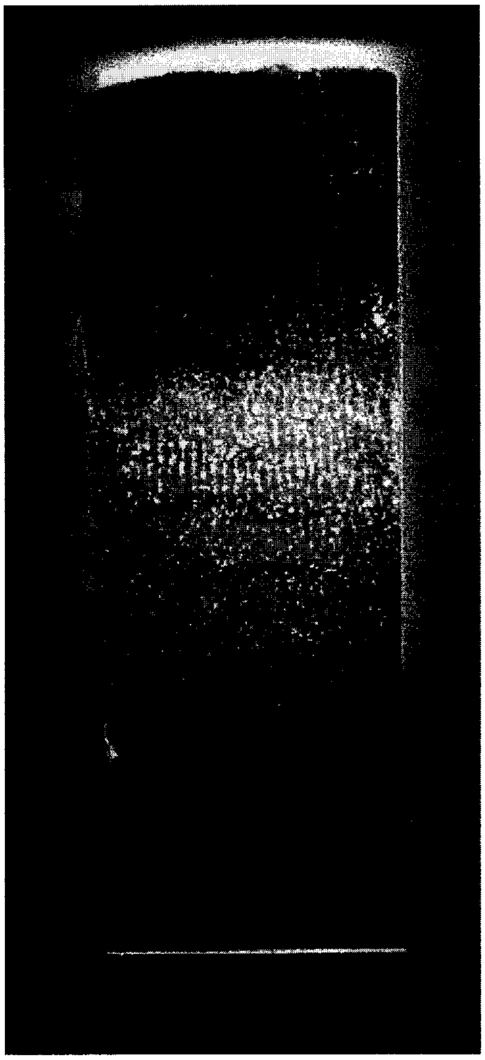


Fig. 4. Erosion of alum plate surface by a standing wave.

solution of gypsum. The jets were directed horizontally from the nozzle and had a diameter of 1 mm and moved at a speed $10\,\mathrm{m\,s^{-1}}$. The jet hit the gypsum plate, perpendicularly, 6 cm from the nozzle. When pure water was used, the effects of the erosion on the point of impact of the jet on the plate were obvious from the very first minute. During the 3 min that the experiment lasted, a crater of 1 mm depth was formed at the point of impact. When using, under the same conditions, a saturated solution of gypsum, no obvious effects of erosion existed on the surface of the plate.

2. Conclusions

The conclusions drawn from the above experimental procedures are:

(a) From the phenomena which are associated with cavitation, the shock waves, which were expected to be very erosive on brittle materials, are not responsible for the cavitation erosion of gypsum and alum because these waves appear in both pure water and in saturated solutions. We also arrived at the same conclusion for the extraordinary temperatures phenomena.

(b) The phenomena that have to be examined more carefully are the microstreaming resulting from the oscillation of the bubbles, and the formation of the jets of liquid during the implosion of the cavities found touching the plates.

(c) The microstreaming from the oscillation of the bubbles has to be excluded as the cause of the erosion because the experiment of the standing wave proved that the erosion occurred on the antinodes of pressure where the bubbles with a less radius less than the critical radius are trapped ($R_r = 4\,\mu\mathrm{m}$ at 0.8 MHz frequency), while larger bubbles that survive longer and could be put into oscillation, migrate and become trapped [4] at the nodes of pressure. It is notable that even in the experiments when we irradiate the plate directly, without using a reflector, a standing wave is always created because the plate itself plays the role of the reflector, forming the antinode of pressure (since the Z of the plate $> Z_{H_2O}$) at the surface of the plate.

(d) The possibility of abrasion due to solid suspended particles is excluded because the solutions used was clear after filtration.

(e) The cause of the erosion is due to the jets created by the asymmetric implosion of cavities, especialy those adjacent to the plate and with a radius smaller than 4 µm. These bubbles have a small duration (of about one period) because they are found in a much more powerful sound field then the one we measured (twice the pressure amplitude measured in the center of the beam). This occurs because the measurement related to the intensity of a traveling wave, not of a standing one, which, as mentioned above, we cannot avoid.

(f) The erosion of the plates is not mechanical due to the jets, but a dissolution of the plate from the continuously renewed solvent at the point of crash of the jets. This was proved by the last experiment described above when we had erosion by using a thin jet of pure water, while no erosion was noticed when a saturated solution was used. If the phenomenon of erosion was mechanical, we would have erosion in both cases.

References

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