AMBIENT LOADING EFFECTS IN CAVITATION PITTING

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ABSTRACT

The mechanisms for formation of, and material removal from, cavitation-induced crater-type pits are discussed. Experimental evidence that material is actually removed from such pits, which are formed under highly transient loading conditions, is advanced. This is opposed to the case of pits formed under semi-static loading conditions from which no material is removed, as verified experimentally.

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In addition, the authors would like to thank the Micrometrical Manufacturing Company of Ann Arbor for the use of their Linear Proficorder, and the following faculty and research personnel of this university: Professors C. A. Siebert and R. D. Pehlke of the Chemical and Metallurgical Engineering Department and Messrs. V. A. Fiss and H. M. Ring.

1) No [illegible] pits

2) Large [illegible]

3) Removal from [illegible] craters (proficorder traces)

4) [illegible] in [illegible] + mechanism of material removal.

5) Possibility of [illegible] by controlled velocity impacts.

1.0 Introduction

It has been previously observed by various investigators[1,2], and also in the previous and continuing investigations at the writers' laboratory[3,4,5], that cavitation damage in its initial phases generally takes the form of individual pits which are sometimes in the approximate shape of symmetrical craters*, and sometimes of quite irregular contour.

It has been postulated by Knapp[1**], and others[2,etc.], and fairly well substantiated in previous reports originating from the present research at the University of Michigan[3,4,5], that these craters are the result of single blows, (in that it was observed that the outline of these pits does not change with additional exposure to cavitation).

It has also been more or less substantiated in a similar manner that the removal of material from the irregularly-shaped pits must also occur as a single event. However, it appears likely that for these pits the structural failures allowing the eventual removal of material is the result of the fatiguing action of many relatively weak blows, and that essentially the precise location and shape of such a pit is the result of localized material parameters rather than fluid-dynamic parameters, (as opposed to the crater pits). The presumed mechanism for material removal from this type of pit, involving a "peeling off" of a surface slab, was previously discussed in papers originating from the overall University of Michigan investigation[3,4].

The present paper is concerned primarily with the crater-type pits. Two outstanding questions regarding these, upon which it is

* ie, a symmetrical impression in the surface surrounded by a raised ridge.

** Knapp assumed that the craters he observed in soft aluminum did not involve weight loss.

believed that some information has been shed by the present investigation, are:

i) Is material actually removed in the formation of such pits?

ii) If so, what is the mechanism of removal?

It is hoped that correct answers to the above may assist in attaining a better understanding of the presumed bubble collapse behavior by allowing a good estimate of the pressure-time regime (as a reasonably precise function of position) which must have been applied to the surface of the material. In this way it may be possible to work back towards a more realistic description of the bubble collapse phenomena.

2.0 Surface Loading Mechanisms

Traditionally it has been supposed that in general, cavitation damage, in those cases where chemical effects are relatively insignificant including the craters presently under discussion, is the result of shock waves transmitted through the liquid phase from a center of collapse within the fluid, and presumably, at a slight distance from the damaged surface. The minimum possible distance from the center of collapse to the surface is approximately the maximum radius which the bubble in question had attained during its lifetime. It is reasonable to suppose that the bubble center cannot move appreciably during collapse. The time involved, for such movement is extremely short, as verified both experimentally,[6,7, e.g.], and theoretically (starting with Rayleigh's initial analysis[8] for an ideal fluid, and including later elaborations to include in varying degree real fluid effects[9,10,11, e.g.]). It has also been shown experimentally by Ellis[12] that only those bubbles, whose center of collapse is originally very near the surface, can create forces large enough to cause the observed damage.

The traditional mode of calculation has assumed spherical symmetry, and under this assumption it can be shown for ideal or for varying degrees of real fluid approximations[8,9,10,11] that, the presence of short range forces sufficient to cause the observed pitting can be justified. However, the existance of spherical symmetry during the critical final stages of collapse has been questioned, and it has been shown[13] that the spherically-symmetrical collapse process is actually unstable, so that a final non-spherical phase of the collapse might be expected.

Experimental substantiation of the non-spherical collapse, and of an alternate damage mechanism (previously suggested by Kornfeld and Suvorov) has been provided, at least for a specific case involving a spark-generated bubble in a static fluid, by Naude and Ellis[15]. Ultra high-speed motion picture sequences were obtained showing the non-symmetrical collapse of hemispherical bubbles attached to a flat plate, wherein the final collapse apparently gave rise to a high-velocity central liquid jet, which impinged on the plate. The forces so generated were indicated by the use of a photoelastic plate material, and it was shown that they were sufficient to cause the type of pitting observed.

Further evidence that cavitation pitting may actually be the result of an impinging high-velocity liquid jet, rather than shock waves transmitted through the liquid*, is furnished by the experi-

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* If the mechanism is shock waves, then it should be possible to create similar pits by explosions and of course the craters generated by explosions either above or below the earth are similar in appearance.

** In these cases the specimens were whirled rapidly through a jet of liquid. It is possible that cavitation may have been generated in the liquid by the high velocities created by the whirling test specimen, and may have contributed directly to the observed damage.

mental fact that pitting caused by impacting droplets[16,17,e.g.], solid particles[16,18,e.g.], or a liquid jet[19,20**] appears to be very similar to cavitation pitting. Compare Figures 1 and 2 and 3 and 4 for instance. Figures 1 and 2 are photomicrographs at the same magnification showing pitting on similar materials caused by water cavitation downstream of a venturi throat[3,4], while Figures 3 and 4 are photomicrographs at the same magnification showing pitting on similar materials caused by a water jet of about 2700 feet per second also from the present investigation. The time of impingement on the particular portion of the surface shown is about 110 & 22 hours in the cavitation tests and about 50 & 50 milli seconds for the impinging water jet.

3.0 Material Removal Mechanisms

Possible material removal mechanisms which have been postulated by the investigators concerned with the impacting liquid droplets or solid particles[16,17,18,21] and which could well apply also to the cavitation crater are:

i) Material "splash" due to the inertia of the material,[21,etc.] as it is displaced rapidly from the center of the crater into the surrounding ridge, exceeding the material strength, and thus allowing material to tear free. Historically, a very early picture of a phenomenon of this type, known as "petalling", and occuring when a solid shot is impacted on armor plate, is shown by Worthington[22]. He refers to the phenomenon as "permanent splash".

ii) Material "wash-out" due to high fluid* velocities[16,etc.]

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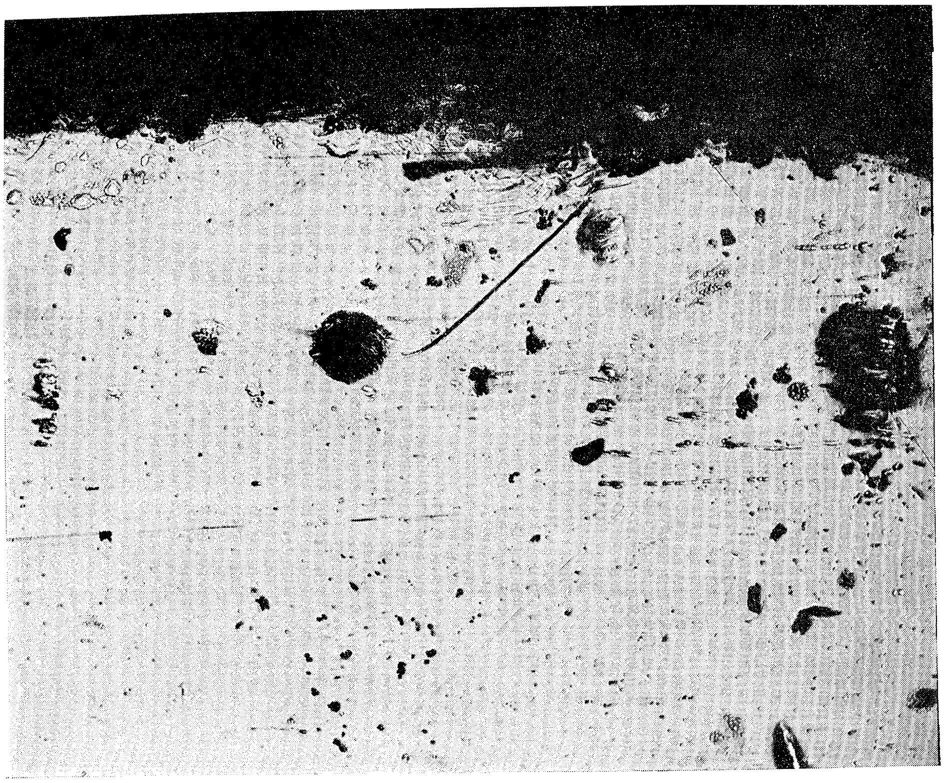
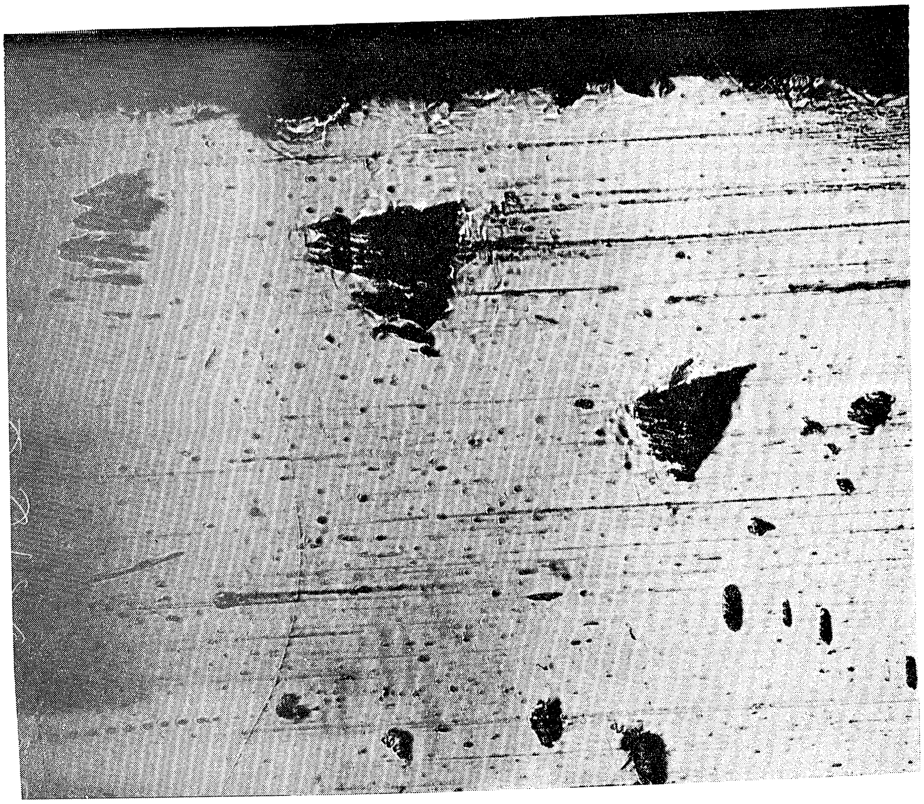
* If the velocity of a solid particle is sufficiently high, the solid behaves essentially as a liquid during the moment of impact. Another somewhat related example of solid material liquification is afforded by the retaining diaphragm in an armor-piercing "shaped-charge".



(a)



(b)

Fig. 1 Cavitation Damage, Material: 302 SS; Throat Velocity: 64.7 ft/sec; Duration of Cavitation: 140 hours; Mag.: 100X; Standard Cavitation, Specimen Number 3-5.

Similar micrograph
for 1010 CS to be supplied

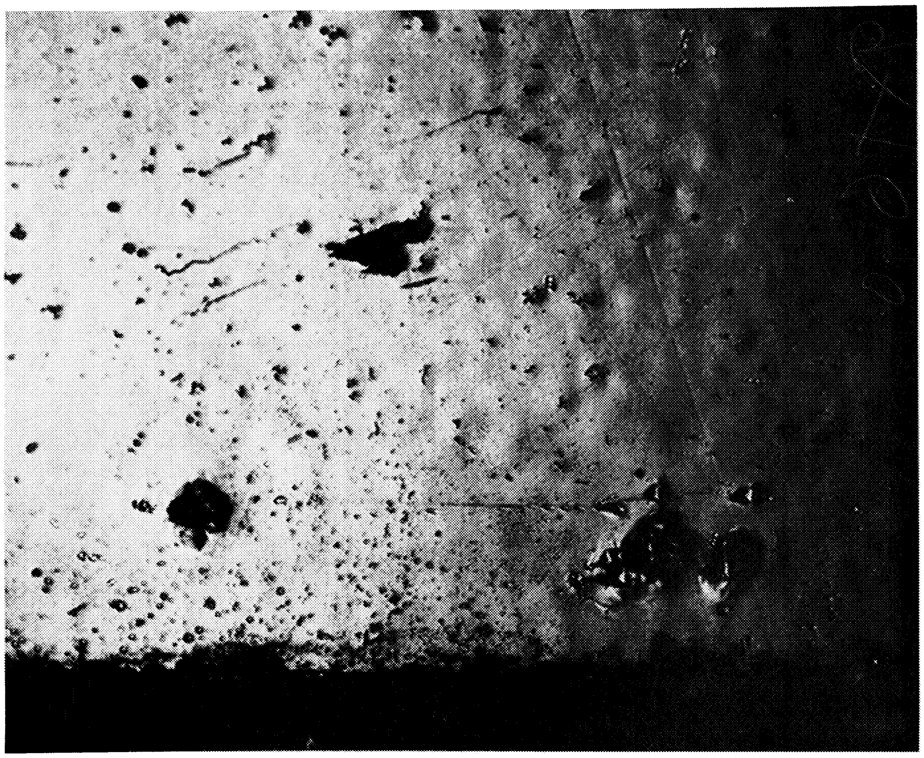


Fig. 4 Cavitation Damage, Material: 1010 CS; Throat Velocity: 64.7 ft/sec; Duration of Cavitation: 22 hours (upper photo), 3 hours (lower photo); Mag.: 100X; Standard Cavitation; Specimen Number 1-19.

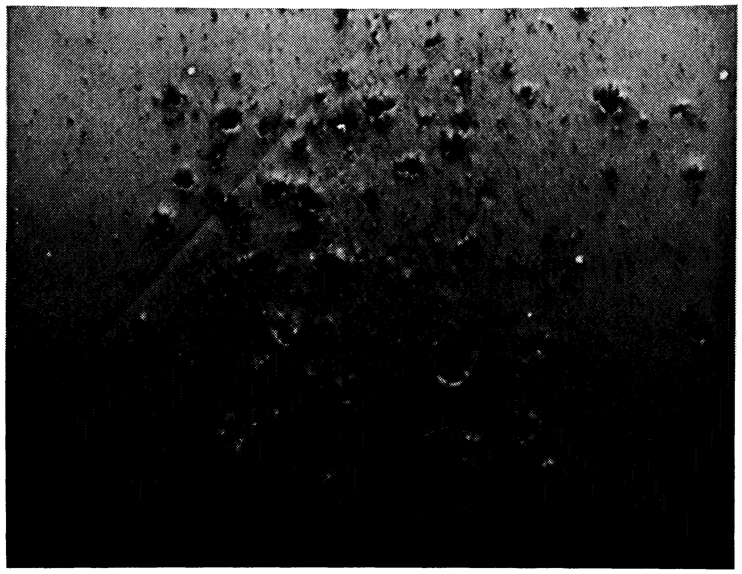


Fig. 13 Damage from Water Jet, Material: 303 SS; Velocity: 2700 fps; Duration of Impingement: 5 millisecs.; Mag.: 120X.

Fig. 14 Damage from Water Jet, Material: 1010 CS; Velocity: 2700 fps; Duration of Impingement: millisecs.; Mag.: 120X parallel to the surface generating very high shear forces with the material, and tearing the surface layers free.

Both of the above are applicable only when the impact of a liquid jet (applicable to either mechanism) or of shock waves (particularly applicable to the material splash mechanism) is of a highly transient nature, so that the rate of loading becomes very rapid. It is obvious that the gradual application of even a very large normal load will not cause material removal, nor in general will the imposition of a low velocity droplet or liquid slug, even of large mass.

4.0 Experimental Observations of Present Investigation

4.1 Semi-Static Loading (Hardness Indentor) Pits

As part of the present University of Michigan investigation of cavitation damage, detailed measurements have been made to determine the disposition of material around several "artificial" craters created by semi-static loading with a hardness indentor[19]. The case wherein the most complete measurements were made was for a pit in annealed austenitic stainless steel plate (applicable mechanical properties are listed in Table I).

Vertical displacements of the plate surfaces, originally optically flat, were measured by a precision "Linear Proficorder".* By numerical integration from the resultant curves, it was found that the volume removed from below the original surface, ie, the "crater", was always equal, within the precision of the measurements, to the volume raised above the initial surface, ie, the "ridge".

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* Manufactured by Micrometrical Manufacturing Company of Ann Arbor, Michigan.

TABLE I

TYPICAL MECHANICAL PROPERTIES OF MATERIALS TESTED

Material	Stainless Steel Type 302 or 303	......	1010 Carbon Steel
Condition	Annealed	......	Annealed
Tensile Strength (psi)	98,000	......	50,000
0.2% Yield Strength (psi)	37,000	......	30,000
% Elongation (in 2 in.)	35	......	40
% Reduction in Area	65	......	71
Hardness			
Measured Rockwell B	76	......	48
BHN (Measured)	140	......	85
Bending Fatigue Strength(psi)	35,000 @ 10^7 cycles	......	25,000 @ 10^7 cycles
Elastic Modulus	28×10^6	......	28×10^6

Thus, as would be expected*, no substantial material** was removed by the semi-static creation of such pits.

A further observation of significance in the case of cavitation craters is that permanent material displacements were observed at unexpectedly large distances from the crater centers. Measurable vertical displacements extended out to approximately 15 to 18 radii from the center of the crater.

Horizontal displacements were also measured, but in a somewhat less precise manner[25]. A plate of the same material was etched, and composite photo-micrographs of the region to be pitted were made before and after the imposition of the hardness indentor. It was found possible in this manner to measure the relative displacement between identifiable points on individual grains before and after the creation of the pit, and thus to determine permanent horizontal distortions due to the formation of the pit as a function of position.*** In this manner permanent horizontal displacements were observed out to approximately 4 radii from the pit center, and slip-lines in the material out to about 7 radii from the pit center.

From the viewpoint of cavitation damage, the above observations are, of course, important in showing that individual pits

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* A simplified theoretical analysis[23,24], based on the assumptions of elasticity showed that the reduction of volume due to the net compressive stresses would not be within the precision of the measurement and would amount to only about 1 or 2% of the crater volume, or 0.06 to 0.12% of the yielded volume. Thus, presumably weight loss can be used as direct indication of volume loss for the weight cavitation pitting.

** Admittedly, traces of material may have adhered to the indentor.

*** This method, similar to one used for the detection of earth movements due to an explosion,[27], could also perhaps be usefully adapted to the measurement of horizontal displacements around an actual cavitation pit.

may affect material properties by cold-working at relatively large distances, and thus influence the location and severity of subsequent pitting.

4.2 Transient Loading (Cavitation) Pits

Linear Proficorder traces were also made of five cavitation craters[5], and it was found that in all cases significant volume was removed, * as contrasted with the semi-static loading pits previously discussed. Figures 5 and 6 show typical proficorder traces. Figure 5 is of a hardness indentor pit, and Figure 6 of an actual cavitation pit. It is noted that the profiles are of generally similar shape, both showing a ridge, except that the hardness indentor pit is relatively substantially deeper (Depth/Diameter=0.13 vs. 0.02 to 0.05 for typical cavitation pits and has a larger ridge (height/diameter=0.018 vs. 0.0006 to 0.02 for cavitation pits). The ridge, ie, raised area, for cavitation pits, extends generally about 1/3 as far from the center as the ridge hardness indentor pits, ie, about 5 radii from the pit center. The difference from the hardness indentor pits is believed due to the relative shallowness of the cavitation pits.

The actual removal of material from the cavitation craters (ie, single-blow, non-fatigue type of pits) is further substantiated by the fact that directly measurable weight loss occurs[4,26] for samples where a substantial portion of the pitting is of this type. The weight loss can be quantitatively estimated by a tabulation of the observed pits[5], and has also been detected by measuring radio-activity from the debris of irradiated test specimens[4,26,28].

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* For the 5 cavitation crater-type pits observed, the average volume loss per pit was 0.67 of volume of the "crater" of the pit.

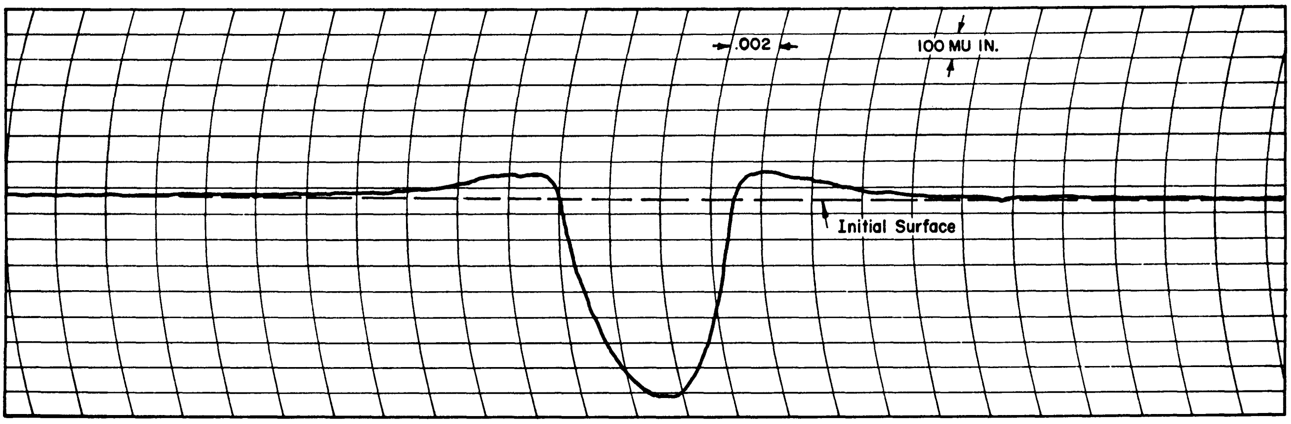

Figure ~~16~~.5 Typical proficorder trace of an artificial pit. Vertical scale: 100 microinches/division. Horizontal scale: 0.002"/division. ½X. Notice how far the ridges extend away from the pit crater, and the approximate symmetry of the ridges about the crater. Taken from McHugh(11).

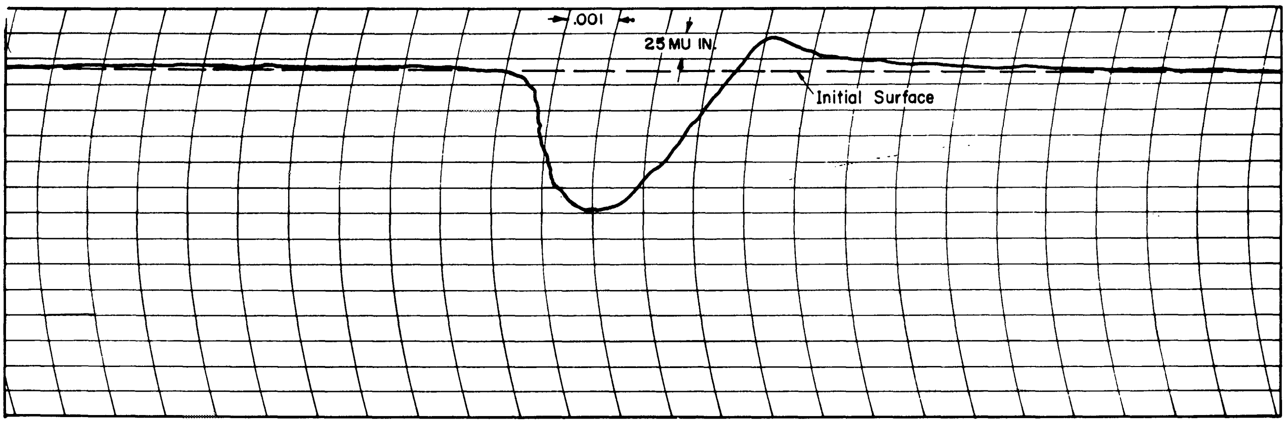

Figure ~~17~~.6 Typical proficorder trace of a cavitation pit. Vertical scale: 25 microinches/division. Horizontal scale: 0.001"/division. ½X. Note the smaller and non-symmetrical ridges (largest ridge is on downstream side of pit) of this cavitation pit as compared to the artificial pit illustrated in Figure ~~16~~.5

The fact that material is removed from the vicinity of the cavitation craters, whereas it is not removed from the region of the similar pits caused by semi-static loading is taken as an indication that:

i) Some mechanism of material removal is operative in the cavitation case.

ii) Very likely one or both of the mechanisms previously discussed are significantly involved.

iii) The highly transient nature of the loading is instrumental in the material removal process.

The removal of material by the impact of high-velocity drops, jets, or particles has been detected by direct measurements by the previous investigators already mentioned[16, 21]. Also, a weight loss of 0.06 mg has been measured in the present investigation, on samples of the size and weight of the cavitation specimens, due to the imposition of a 2700 feet/second jet of water for 30 seconds on a test specimen of 303 SS and a weight loss of 0.79 mg due to the imposition of the same water jet for 24.5 seconds on a test specimen of 1010 carbon steel. (Mechanical properties as listed in Table I.)

5.0 Desirable Approaches for Further Definite Tests

Two approaches, both of which it is expected to follow in the present investigation, are:

5.1 Effect of Rate of Loading

Experiments investigating the effect of rate of loading on the material displacements and volume removal around pits created by solid or liquid impact, but generally similar in appearance to cavitation-induced pits, would be most instructive. The end points of the spectrum of possible loading rates of interest (cavitation pits proper and hardness indentor pits) have essentially already been investigated as reported in the present paper. Variable loading rate experiments could be accomplished using jets, drops, or solid particles for which the impacting velocity could be controlled. Measuring techniques would include high-speed motion pictures, and surface displacement measurements as already described.

5.2 Application of Theoretical Bubble Dynamics Analyses

Bubble dynamics analyses now underway in connection with the present investigation, and also the various analyses of other investigators could perhaps be applied to compute the anticipated order of impulse expected to be applied to the surface, considering the various modes of bubble collapse. This information, together with the measured material displacements in the vicinity of the cavitation pits, and the observed numbers and sizes of bubbles and measured pressures, may aid in determining more closely the actual mechanism of bubble collapse.

6.0 Conclusions

It is felt that the most significant conclusions from this paper are the following:

i) Pits, quite similar in appearance to cavitation pits of the crater-type, are also formed by impacting liquid droplets, jets, solid particles, and also by explosions. It is possible that the same mechanisms for material displacement and removal (ie, material "splash" and "wash out" are operative and significa t in some or all of these cases.

ii) Whereas material is not removed by pits produced by semi-static loading, it was removed from all the cavitation craters observed during the present investigation, and from pits created by the other forms of highly transient loading listed under (i) above. Plausible mechanisms for such material removal are discussed in the paper.

iii) Significant new information regarding the mechanism of cavitation pitting may be obtained by observing the effects of high rates of loading on material displacements and volume removal, and also perhaps by correlating bubble dynamics analyses, and observations on number and sizes of bubbles and local pressures with the observed material displacements around actual pits.

iv) The range of cold-working effects from individual pits probably extends as far as 5 radii from the center of a crater-type cavitation pit (compared to about 15-18 radii for the relatively deeper hardness indentor pits).

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