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Damage to Solids Caused by Cavitation

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XXII. Damage to solids caused by cavitation

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[Plates 50 and 51]

This paper describes the early stages of cavitation damage observed in cavitating venturi tunnels. The cavitating fluids were water and mercury, and a wide range of specimen materials were used. The damage was found to consist of single-event symmetrical craters and irregular fatigue-type failures. The degree of damage was highly sensitive to minor flow perturbations, and this is discussed. The effect of stress level in the specimen before testing, and relations between cavitation resistance and the mechanical properties of the materials are considered.

Introduction

In this Discussion I shall confine myself primarily to problems arising from our own laboratory experiments. The equipment in use includes two small, high speed, tunnel-venturi facilities, one using water and one mercury, and a 20 kc/s vibratory unit which has been operated with water, mercury and lead-bismuth alloy (Hammitt 1964; Garcia & Hammitt 1965).

We have felt that the major objective of such research was to attain a position whereby an *a priori* prediction of the damage to be expected in a prototype facility would be feasible. We feel that this can best be accomplished by using a flowing system, wherein the conventional fluid flow parameters of pressure, velocity, and temperature can be measured, and have a meaning similar to that in a prototype machine as a pump, turbine, etc. As a good compromise amongst the various alternatives, we selected a venturi. Damage test specimens could then be inserted into the cavitating region.

We also have constructed a vibratory facility primarily for testing with fluids and/or temperatures unattainable with the tunnel facilities. However, the present paper is concerned mainly with the venturi devices, since these are more closely related to flow machinery.

Damage in flowing systems

(*a*) *General*

The cavitating venturis we have used have differed only in the circumferential arrangement of damage specimens, and in the material of construction, i.e. plexiglas and stainless steel.

(*b*) *Single-event pitting*

(1) In the early phases of damage we observed two types of pitting:

(i) 'Crater' pits,[†] which, because of their symmetry and general appearance, are presumably formed by a single bubble implosion. The traditional mechanism for the

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[†] Among the earlier published observations of such pits are those by Knapp (1955) in a water tunnel and in a hydraulic turbine passage (1958). More recently, in addition to our own observations (Hammitt 1963; Hammitt *et al.* 1966), a similar type of pitting has been reported by Varga & Sebestyen (1964) on lead in a tunnel test, and by Wood on stainless steel in a centrifugal pump.

imposition of damaging forces on such a surface is through the radiation of shockwaves from a bubble collapse and/or subsequent rebound. A competing mechanism which has been suggested (Kornfeld & Suvorov 1944; Naudé & Ellis 1961) is that of the impact of a liquid jet formed during the collapse.

(ii) Local fatigue failure, i.e. irregularly shaped shallow pits, presumably caused by repeated loadings from less energetic bubbles. These are presumed to be also single-event failures, since the size and shape of the pits do not change with subsequent testing.

Figure 1, plate 50, comprises two photomicrographs showing both 'crater' and 'fatigue-type' pits after a given test duration. Neither their shape nor their depth profile (as shown by detailed 'proficorder'† tracings (Hammitt 1963)) change during additional testing, and this is taken as strong evidence that these pits are indeed 'single-event' failures.

The 'crater-type' pits caused (in most of the cases which were examined) by room temperature water on stainless steel, typically had a depth to diameter ratio between 0·07 and 0·02. However, figure 2, plate 50, shows a microsection of a crater incurred in Cb–1 % Zr alloy by room temperature mercury with depth/diameter ratio of about 0·25, showing the effect of a possibly larger force imposition on a somewhat weaker material. Also, crater-type pits of a large depth to diameter ratio have recently been observed on stainless steel in a centrifugal pump test in a high temperature alkali metal (G. M. Wood, personal communication). Assuming that the forces from such alkali metal and from room temperature water may be roughly similar, but that the mechanical properties of the stainles steel are considerably reduced at elevated temperature, these observations may not be inconsistent.

In the venturi tests, it has generally been observed that a ridge is raised around the craters, of a considerably smaller height than the crater depth, and, in the great majority of cases observed (about 90 %), predominantly on the downstream side of the crater. The explanation for this non-symmetry of the ridge suggests that the craters are formed by single-bubble implosions.

Figure 3, plate 51, shows a relatively large crater, as well as numerous smaller pits of both types, formed in stainless steel by cavitating mercury in one of the passages of the centrifugal pump used to drive the mercury loop. This, and the previously cited observations by Knapp and Wood indicate at least some similarity between the cavitation phenomenon as observed in the venturi and as it occurs in turbomachinery.

The detailed observations of pitting from the venturi tests suggest that the early pits are random in their location and size (up to about 50 m in., figure 3). The existence of already incurred damage does not affect the location of new pits. However, as shown by figure 4, plate 51, if pits are large enough, they are capable of causing localized cavitation, and hence, a damage 'wake'.

The number density of pits increases, as far as our observations are concerned, without limit as the size decreases. These facts suggested (Hammitt 1963) a bubble energy spectrum‡ (figure 5), where the ordinate is the number of bubbles, $n(E)$, from those 'in the

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† 'Linear Proficorder', Micrometrical Division, The Bendix Corporation, Ann Arbor, Michigan.

‡ As pointed out by A. Thiruvengadam in his discussion of Hammitt (1963), there is also a spectrum of energy *absorbed* by the material, which may of course differ from the spectrum of energy *delivered* by the bubbles.

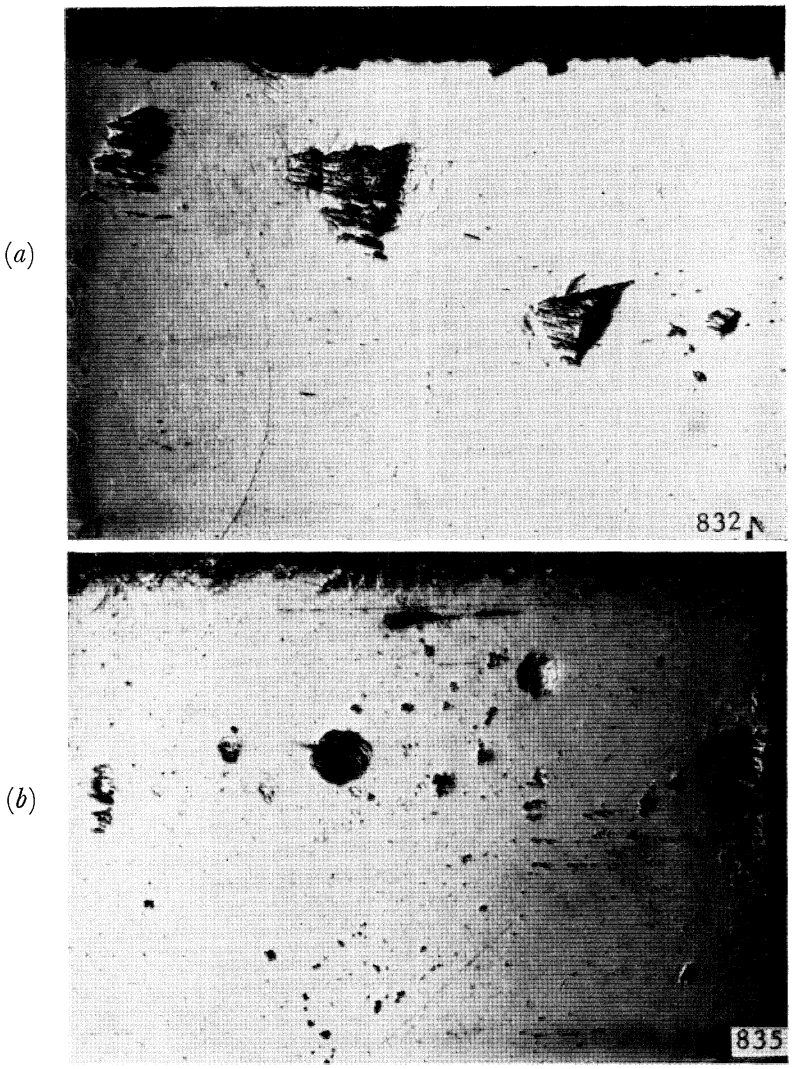

Figure 1. Development of cavitation damage at two locations on 302 stainless steel with water (after 15 and 30 h) standard cavitation. Actual width of views shown is approximately 46·5 m in.

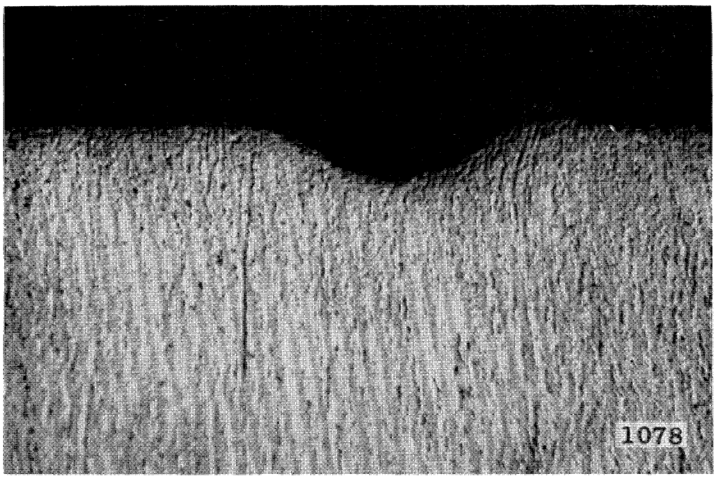

Figure 2. Microsection through cavitation pit (shown in figure 4) for 'nose' cavitation in mercury at a throat velocity of 48 ft./s. Duration 50 h. Material is columbium–1 % zirconium. Etched. (Magn. × 800.)

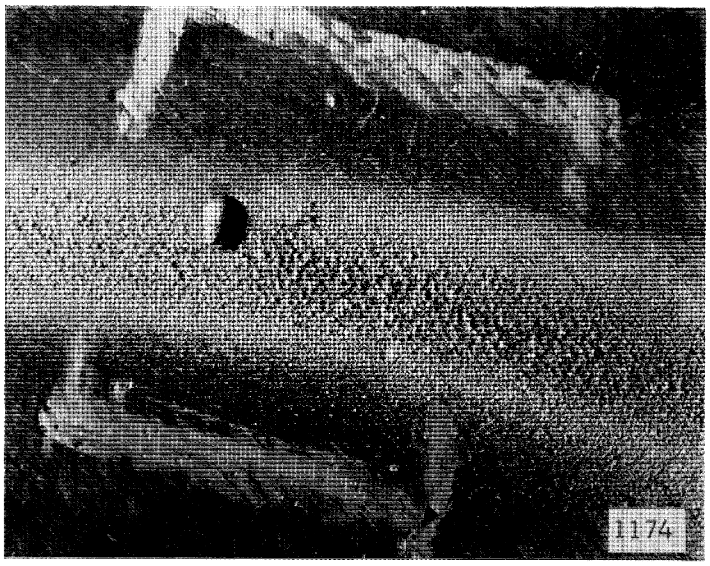

FIGURE 3. Cavitation damage on back shroud of two-piece impeller after 596 h exposure to cavitating flow in mercury. (Magn. × 5.)

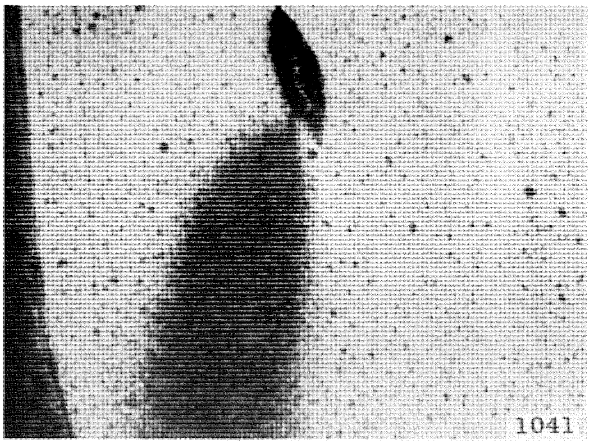

FIGURE 4. Cavitation pitting in columbium–1 % zirconium after 50 h exposure to 'nose' cavitation in mercury at a throat velocity of 48 ft./s. (Magn. × 100.)

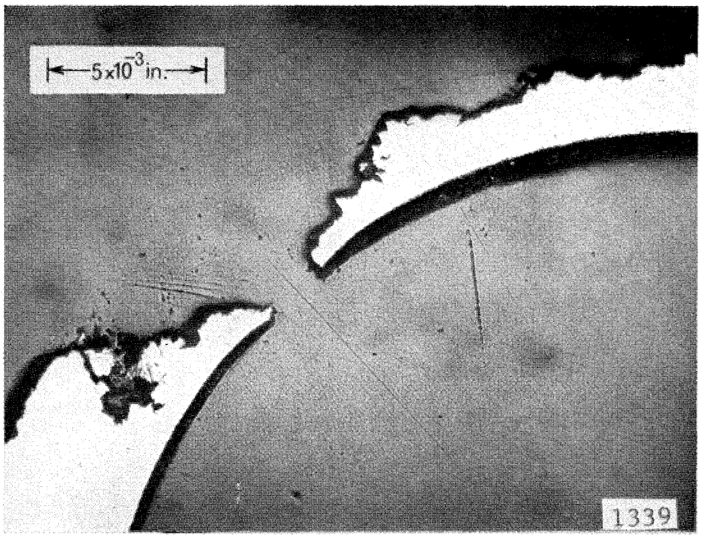

FIGURE 8. Metallographic cross section through stainless steel pin specimen wall. (Magn. × 40.)

vicinity' of the damage specimen which deliver upon their collapse, an energy quantum, E, to the surface. As indicated by figure 5 for the particular case of a cavitating venturi, the number of bubbles will increase as the 'degree of cavitation' is increased but their mean energy, and hence capability of causing damage, will decrease. A hypothesized threshold damage energy for a given material is shown in the figure. (The labelling of the curves is as explained in Hammitt (1963), but generally shows an increase in the extent of the cavitating region as one moves away from the 'sonic initiation' and 'visible initiation' curves.)

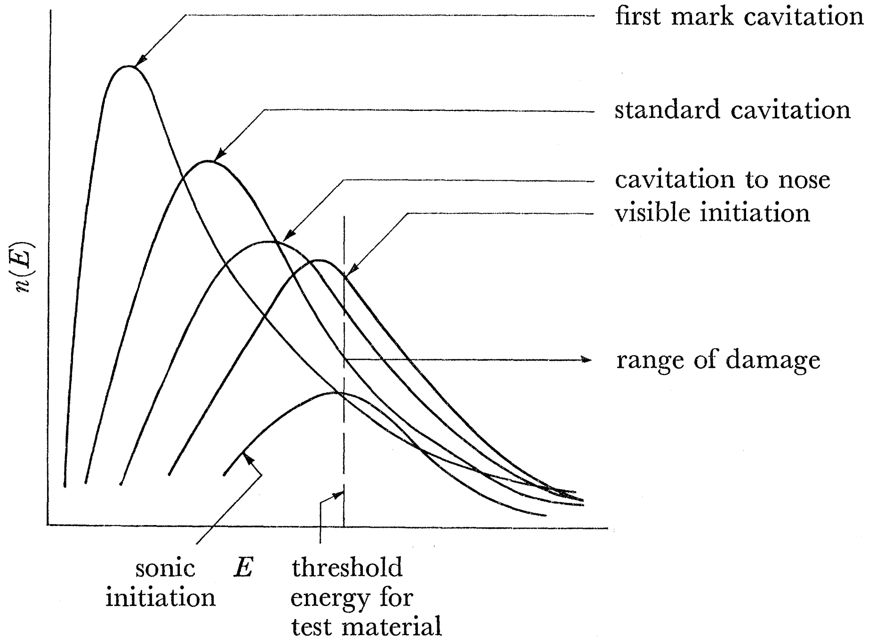

FIGURE 5. Hypothesized bubble energy spectra for various cavitation conditions at a constant velocity for a given material.

The randomness of the pitting is taken further to indicate that no 'incubation period' exists for crater-type pits if the method of observation is sufficiently precise. This has been verified not only by the pitting observations, but also by detailed surface measurements (Hammitt *et al.* 1964) and by the use of an irradiated test specimen (Walsh & Hammitt 1962) which showed a weight loss starting from essentially zero time (figure 6). Possible mechanisms, typically considered for removal of material by liquid impact (Engel 1953, 1958) are metallic 'splash' due to the highly transient nature of the surface loading, or 'wash-out' due to high transverse velocities.

The fatigue-type pits do suggest an 'incubation period', but only for that specific mechanism. Thus for a system where this phenomenon was predominant, an incubation period could possibly exist.

(c) *Rate of cavitation damage*

The venturi tests indicate a highly time-dependent rate of damage (Hammitt 1963; Hammitt *et al.* 1966). Almost uniformly a high initial rate is observed followed by a considerably decreased rate, but then increasing again to subsequent peaks in the curve of rate against time. We ascribe the early rate peak to surface imperfections, inclusions, or other 'weak spots', rather than to fluid dynamic effects. However, we feel the later nonlinearities are primarily due to the perturbations of the local flow pattern by the roughened surface, and to a lesser extent to changes in the surface microstructure due to work-hardening, etc. We have observed such an increase in microhardness in some work-hardenable materials, as may also have been observed elsewhere.

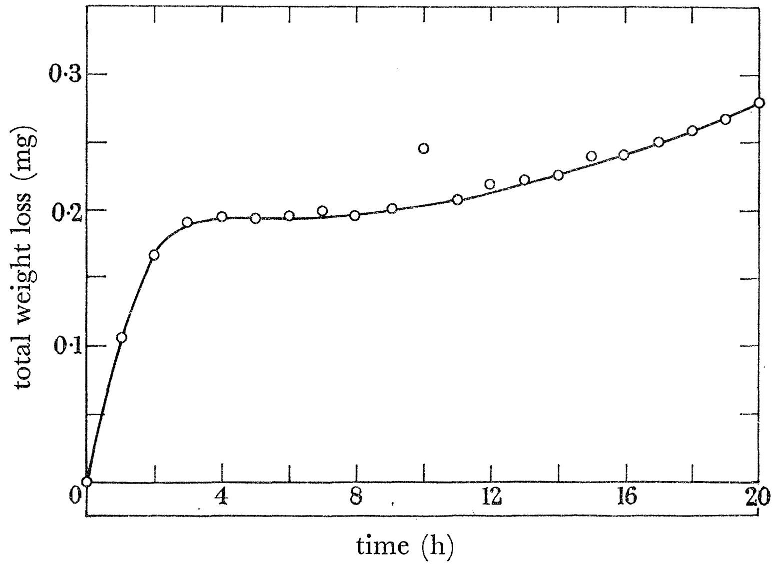

Figure 6. Total weight loss plotted against duration for stainless steel at 'standard' cavitation in water at a throat velocity of 70 ft./s as determined by observations on radioactive debris from irradiated specimens.

(d) *Sensitivity to minor system variations*

We have found that the rate of cavitation damage for a given flow system, geometry, fluid-material combination, temperature, velocity, and overall 'degree of cavitation' can be changed by an order of magnitude by apparently minor system variations. Among the variations which we find can have a significant effect in our own facility are the following:

(i) *Orientation and number of test specimens*

Of the three specimen orientations used, two were symmetrical and the third was not. Non-symmetrical pitting distributions have been noted (Hammitt *et al.* 1966), wherein the flow has appeared to cross a side-edge of the specimens, coming from the relatively restricted region between the specimens.

Detailed pressure measurements made along the polished face of a test specimen (Hammitt *et al.* 1965; Robinson 1965) indicate a strong dependence on the number of the specimens. Since it has been observed (Hammitt *et al.* 1966) that the most damage occurs in the regions wherein substantial pressure recovery from the minimum around the nucleation region has already occurred† it would be expected that the specimen arrangement might substantially affect the damage rate.

(ii) *Fluid purity*

It has long been recognized that relatively large quantities of entrained gas may well substantially reduce cavitation damage. It is indicated by the present tests that small

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† Electrical conductivity measurements through a microprobe indicate that the fluid is essentially 100 % (volume–time mean) liquid at these damaged points.

quantities of water in mercury may increase damage significantly (even to relatively non-corrodible materials such as stainless steel), whereas larger quantities of water may well reduce it. The very preliminary data of figure 7 indicates a maximum damage capability at about $1500/10^6$ of water in mercury. The effect of small quantities of water is presumed to be through the competing mechanisms of increasing the effective vapour pressure of the fluid, and thus promoting growth and nucleation, while at the same time perhaps cushioning the collapse. It is believed that the effects of small quantities of gas may be somewhat similar. A decrease in damage with increased dissolved gas has been shown for a vibratory test (Bebchuk & Rozenberg 1960).

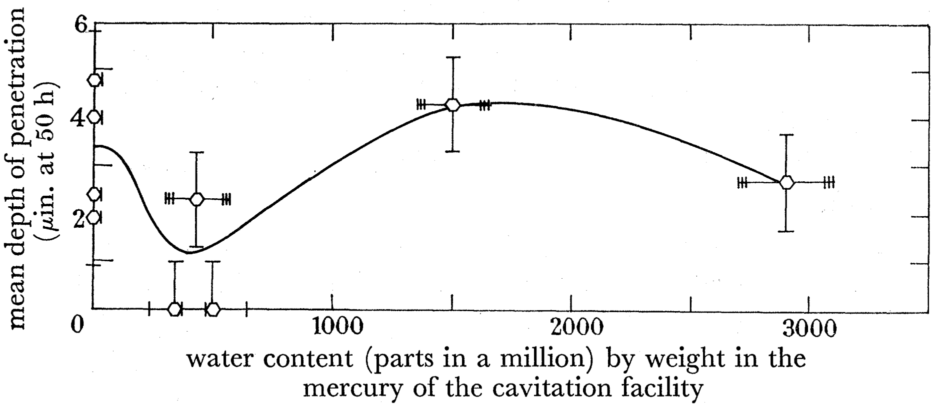

FIGURE 7. Mean depth of penetration plotted against water content (parts in a million) in mercury.

(iii) *Venturi roughness*

It appears that damage rates are considerably greater in partially damaged venturis, leading to the suspicion that strong vortices must be formed near the trailing edges of the test specimens, which cause considerable damage to the specimens. Examination of some of the more heavily damaged specimens where the damage appears concentrated around the trailing edge (which has actually been reduced substantially in length) tends to confirm this belief.

(iv) *Type of specimen*

In some tests, a small pin-type specimen, positioned across the stream and with axis normal to the flow, has been used in place of the 'plate' specimens at approximately the same location in the diffuser. The flow conditions have been adjusted so that the cavitation region terminates around the downstream half of the pin. Severe cavitation vortices are thus created adjacent to the pin, and caused to collapse nearby by the strong axial pressure gradient caused by the venturi diffuser. This specimen variation caused an increase of damage rate of the order of 300. Figure 8, plate 51, is a microsection through one of the pins in which a hole was eroded in the 20 m in. wall in a 5 h test in mercury.

Somewhat similar damage tests have been previously reported (Varga & Sebestyen 1964; Bebchuk & Rozenberg 1960) in which damage was observed not on the pin, but on lead plates embedded downstream in the walls of a water tunnel test section.

The above indications from a laboratory device strongly support the supposition that apparently relatively minor changes in the geometry or other conditions of a turbomachine can change cavitation damage rates by order of magnitude. Further, it is indicated that the imposition of vorticity upon an otherwise essentially translatory flow can increase damage potential tremendously.

(*e*) *Fluid velocity effects*

Previous investigations have shown that cavitation damage increases approximately as the sixth power of the velocity increment about a 'threshold velocity' below which no damage occurs (Knapp 1955). This approximate relation has been roughly confirmed in several different types of facilities:

(1) Cavitation upon an ogive in a water tunnel (Knapp 1955).

(2) Liquid jet impinging upon rotating test specimens (Hobbs 1961).

(3) Rotating disk with through-holes as cavitation inducers (Lichtman 1962; Kelly, Wood & Marman 1963).

(4) Cavitation behind a pin transverse to flow in a water tunnel (Varga & Sebestyen 1964; Shal'nev 1955).

We feel that the appearance of a threshold velocity is to some extent a function of the precision of damage observation, i.e. the more precise the observation the lower the threshold velocity would appear to be. If, for a given experiment, a lower threshold velocity is assumed, the power to which the velocity increment above that threshold must be raised to fit the experimental data (which is usually at best a rough fit), also becomes lower.

In our tests, the velocity exponent, defined as above and based on throat velocity with zero threshold velocity, depends on the 'degree of cavitation', since this affects the static pressure profile in the vicinity of the test specimens. The exponent then varies from about zero (or less) to 5 for some tests. In many cases the exponent varies widely over the range tested. Figure 9 shows typical results for mercury (Hammitt *et al.* 1966). The 'cavitation conditions' listed in the legend are in increasing order of extent of cavitating region.

We have explained this behaviour in the following manner. For the well developed cavitation conditions, the entire damage specimen sees essentially vapour pressure at all velocities, and hence the collapse violence is not a substantial function of fluid velocity, leading to the essentially zero damage exponent observed in these cases. For cases where the cavitation region terminates well forward on the specimens, the pressure along the remainder of the specimen is substantially above vapour pressure by virtue of the venturi diffuser. The static pressure, then, over part of the specimen, is strongly a function of fluid velocity in these latter cases, leading to the higher exponents which are observed. The distribution and size of pits found on damaged specimens are consistent with the above explanation. They showed a large number of small pits in the regions exposed to low static pressure, and a smaller number of larger pits in the region further downstream where the pressure is higher, i.e. the driving pressure for collapse is greater and only the larger bubbles penetrate the high pressure region, thus causing fewer, larger pits.

(*f*) *Prestressing effects*

Since cavitation-erosion involves in many cases a predominantly mechanical attack, it is logical to suppose that the rate of damage will be affected by the stress regime existing in the structural member prior to attack. This is a practical consideration because substantial stress levels may well exist in many fluid-flow components, and because it may be possible to inhibit or enhance cavitation damage by a suitable prestressing of the surface.

Figure 10 shows the presumed rate of stress around a cavitation crater, including zones of both tensile and compressive loading. Assuming as a first approximation the maximum shear stress failure mode, the failure criterion becomes the maximum absolute magnitude

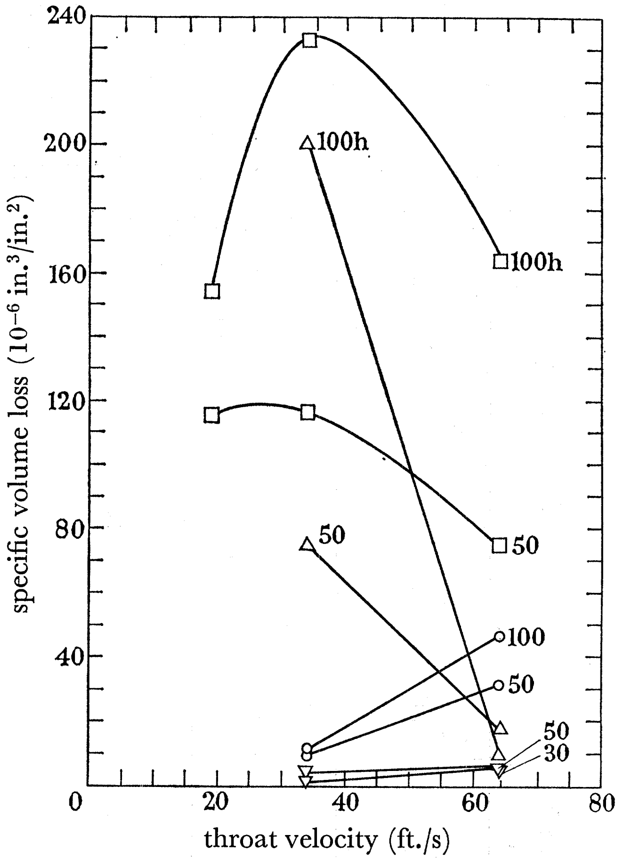

FIGURE 9. Actual specific volume loss plotted against throat velocity for constant time and various cavitation conditions for stainless steel in mercury: ▽, visible initiation; ○, cavitation to nose; □, standard cavitation; △, cavitation to back.

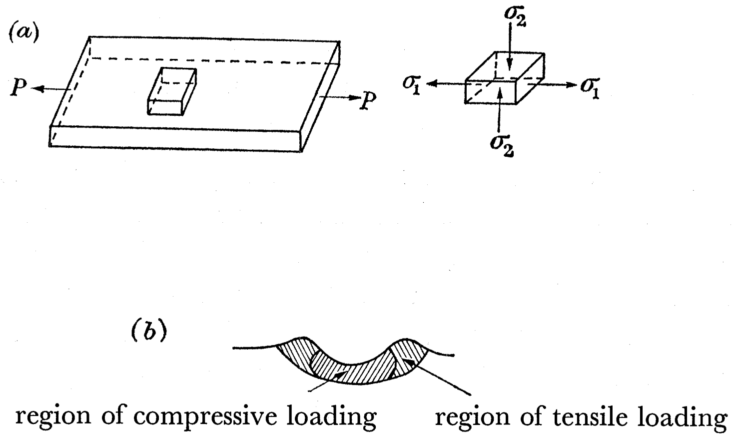

FIGURE 10. Sketch of possible stress distribution under a typical cavitation pit: $\sigma_{\text{failure}} = |\sigma_1 - \sigma_2| < |\sigma_1|$ when σ_2 is tensile, σ_1 being the stress due to the applied load P, and σ_2 the normal stress due to bubble implosions.

of the difference between principal stresses. As indicated in figure 10, the likelihood of failure under cavitation attack, if it occurs due to excessive tensile load (around the crater rim) will be increased by imposition of a uniaxial compressive load, and vice versa. Hence, cavitation testing of prestressed specimens would shed light on the failure mechanism.

A preliminary series of tests of stainless steel specimens under varying degrees of tensile load (ranging up to 1·3 × the yield strength) has been completed (Barinka, Hammitt, Robinson, Pehlke & Siebert 1964). The specimens were thin plates held across the venturi in the location of the conventional specimens, and loaded by an external clamp. They were so designed that they could be pulled in a tensile machine at the completion of the cavitation test, so that effects upon the stress–strain curve could be measured.

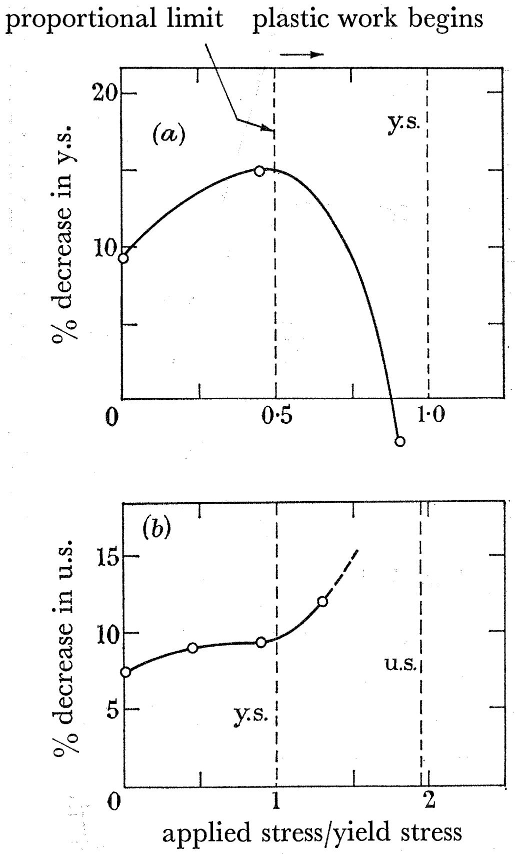

FIGURE 11. Effect of cavitation damage plotted against applied stress on yield strength and ultimate strength of stainless steel.

The following results were obtained from these preliminary tests:

(1) The effect of the applied tensile stress on cavitation damage rate was small, although the damage was increased slightly by the larger applied stresses (about 8 %).

(2) The applied tensile stress in combination with cavitation caused a decrease in ultimate strength which became more substantial as the applied stress was increased (much more rapidly than an estimate based on mean depth of penetration would indicate). The effect is shown in figure 11 where the correction to the strengths for changes in damage are negligible. Also as shown in figure 11, the yield strength decreased after cavitation for relatively moderate applied loads, but increased for applied loads above the proportional limit, no doubt due to cold-work caused by the applied loads.

(3) The effect upon yield and ultimate strengths of a measured mean depth of penetration due to cavitation attack has been measured, and found (for the unstressed specimens) to agree approximately with an estimate based on actual localized depth of penetration. An estimate based on mean depth of penetration would, as assumed, seriously underestimate the actual weakening of the specimen. The increased loss of ultimate strength for the specimens cavitated under an applied load (and for the yield strength also for applied loads below the proportional limit), above and beyond that estimated from depth of penetration, is thought perhaps to be due to the increased growth of microcracks under the applied load. The hypothesis has not yet been substantiated by actual examination of the specimens.

(4) No creep of the specimens under cavitation attack was found even for the maximum applied load.

(*h*) *Material–fluid property damage correlations*

A major objective of cavitation damage research is the determination of a grouping of material, fluid, and flow parameters which could be used to correlate cavitation damage and hence allow its *a priori* prediction. For the present certain limiting assumptions must be made, as, for example:

(1) Limitation to a single type of cavitating flow régime, with a single fluid under fixed conditions.

(2) Considering that only mechanical damage effects are significant (an equally permissible alternative assumption for certain cases would be that only chemical effects were significant. However, the first assumption is more applicable to our venturi tests).

Correlations with various single properties as tensile strength, surface hardness, yield strength, endurance limit, etc., have been suggested by numerous investigators in the past (for example, Botcher 1936; Mousson 1937; Nowotny 1962) and more recently a possible correlation with strain energy to failure has been emphasized (Thiruvengadam 1963; Shal'nev 1962).

Since the pits we have observed appear to originate from two competing mechanisms (i.e. single-blow cratering and fatigue failure), it is not reasonable to expect precise correlations against a single mechanical property to be possible. However, we feel that the strength and energy properties of a material are important.

Both these types of properties are involved in most cases of cavitation damage, so that an idealized material of very high strain energy and low strength; or conversely, one of very great strength, but low energy, could present high resistance to cavitation damage. For materials such that strain energy increases with strength an increase of either type of property would result in increased cavitation resistance. Stainless steels and various refractory alloys which we have tested are of this type.

On the other hand, for some materials, as strain energy is increased, strength properties decrease. Various Cu–Zn–Ni alloys which we have tested are of this type. The results of these tests confirm these suppositions, and show that a 'trade-off' between strength and energy properties in terms of cavitation resistance exists.

Conclusions

In general it is still not possible to predict the cavitation damage to be expected in a prototype machine from laboratory tests. However, progress is being made toward attaining this capability by observing and measuring in laboratory set-ups the effects due to different system variations, and thus obtaining a fuller understanding of the nature of the phenomenon than exists at present. It has become apparent that relatively minor changes in the flow system create order of magnitude changes in cavitation damage rates. For this reason it is necessary that laboratory tests model prototype systems as closely as possible.

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In addition the writer wishes to thank all the various personnel of the laboratory for their assistance in the work on which this paper is based, and particularly Mr M. John Robinson, Assistant Research Engineer, for his additional assistance in preparing the paper itself.

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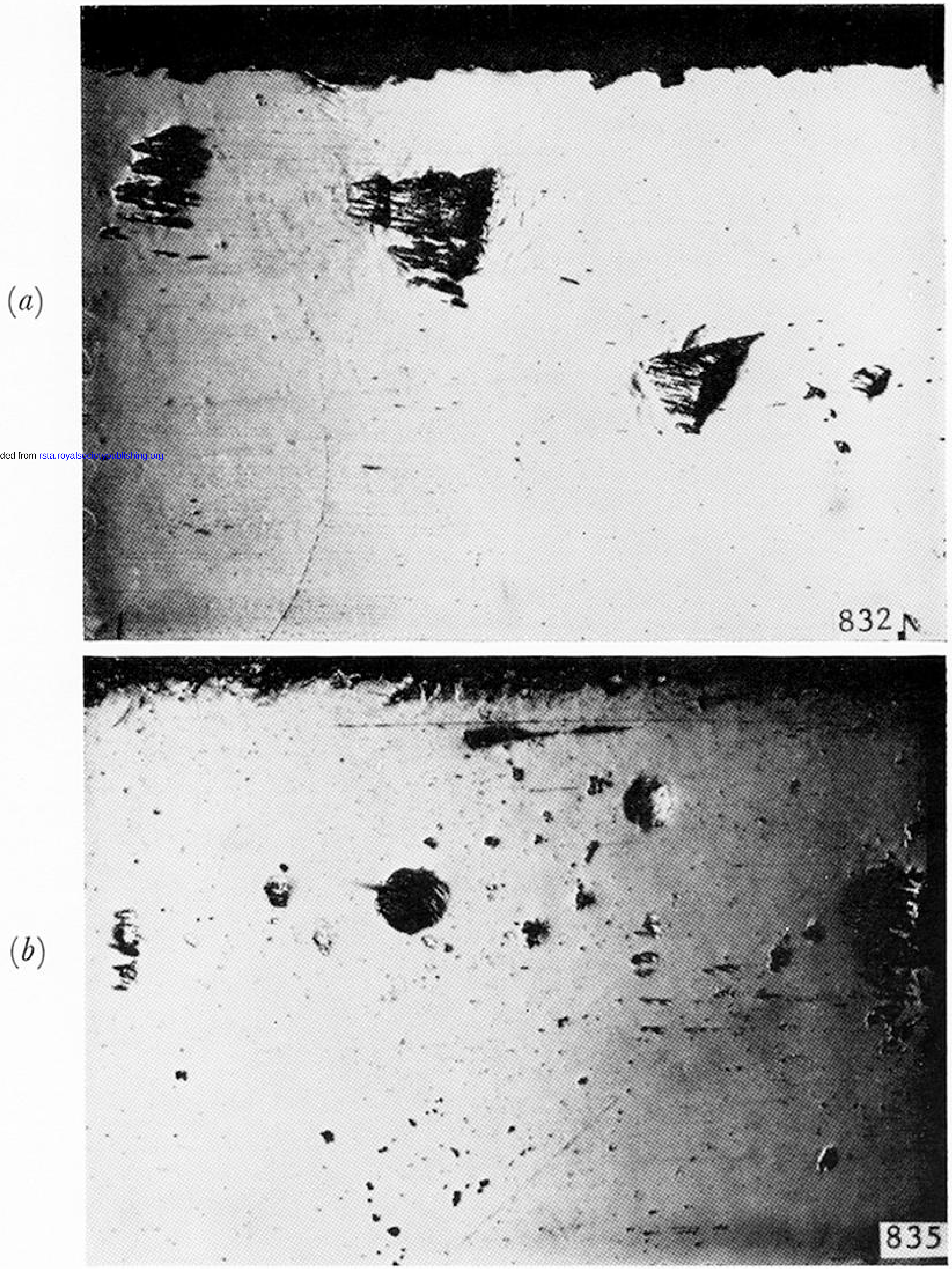

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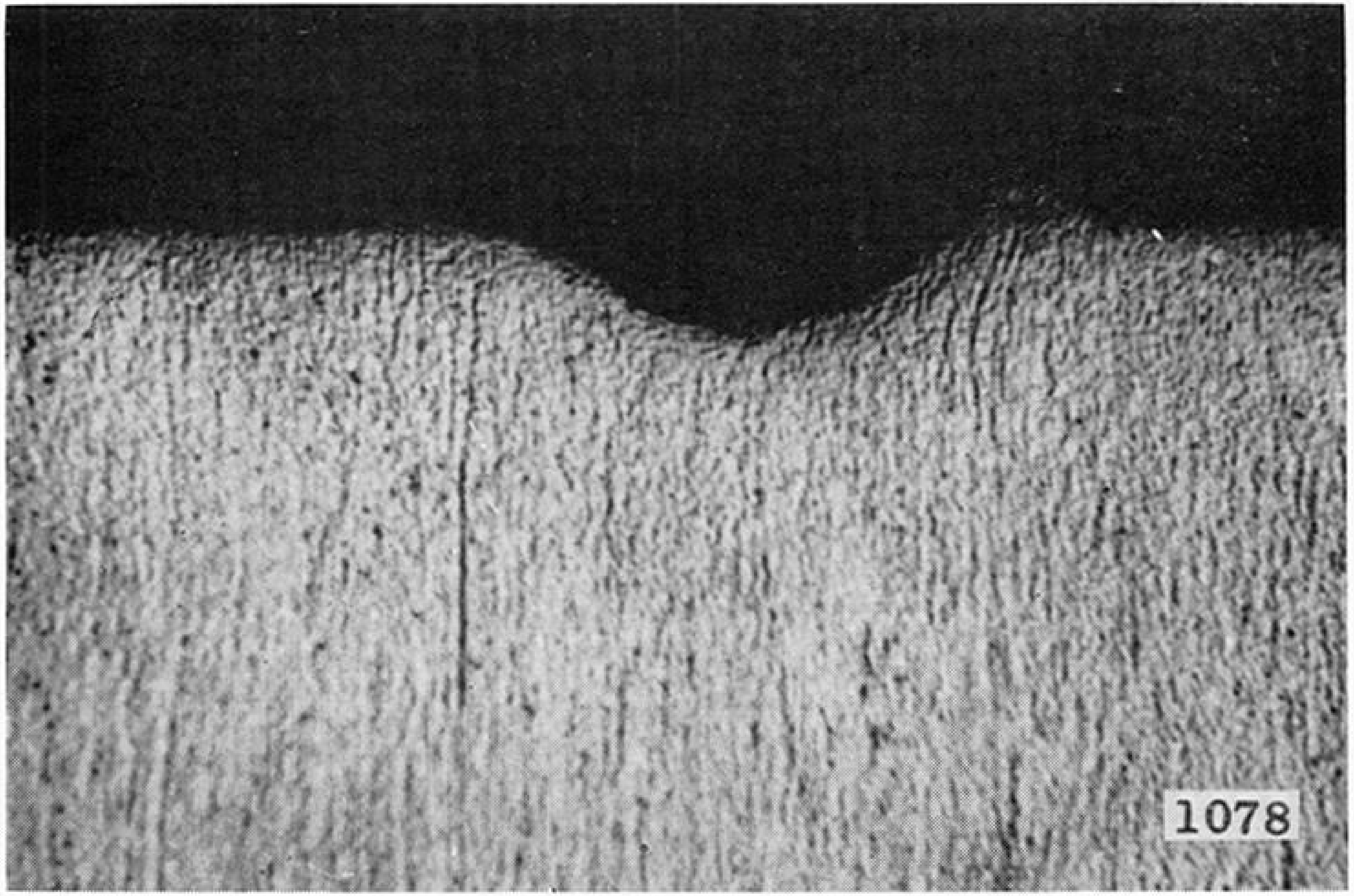

IGURE 2. Microsection through cavitation pit (shown in figure 4) for 'nose' cavitation in mercury at a throat velocity of 48 ft./s. Duration 50 h. Material is columbium–1 % zirconium. Etched. (Magn. × 800.)

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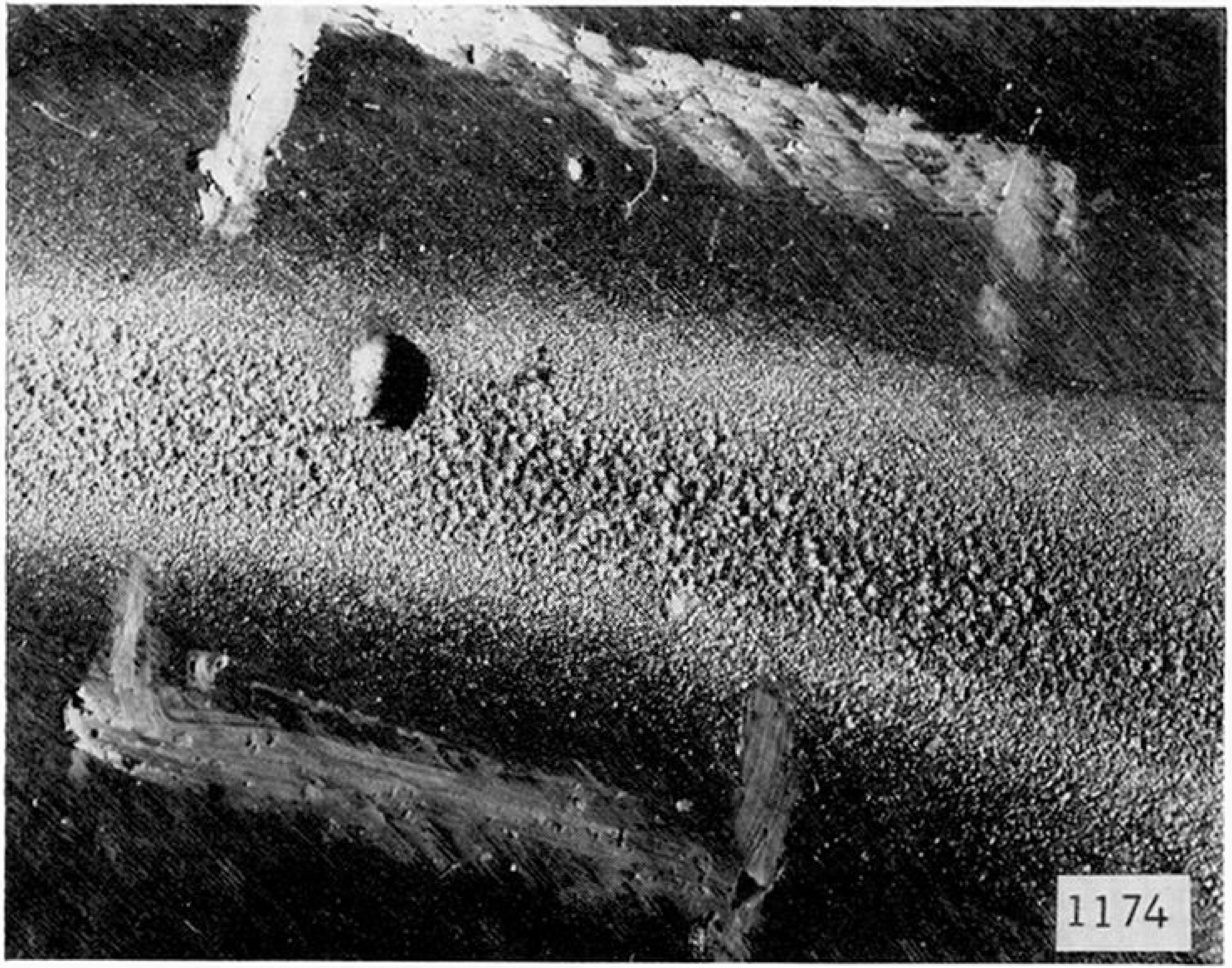
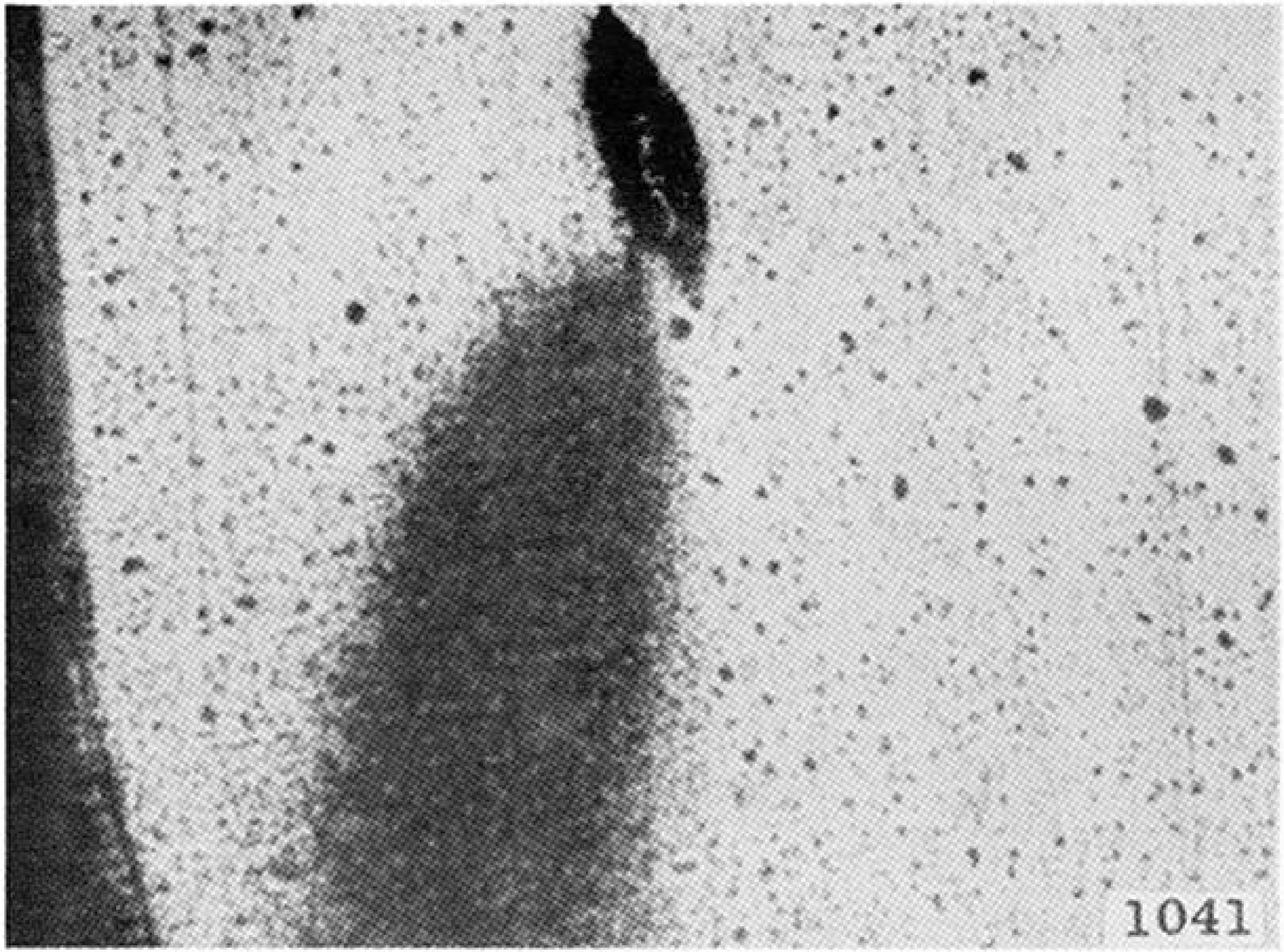


IGURE 3. Cavitation damage on back shroud of two-piece impeller after 596 h exposure to cavitating flow in mercury. (Magn. × 5.)



IGURE 4. Cavitation pitting in columbium–1 % zirconium after 50 h exposure to 'nose' cavitation in mercury at a throat velocity of 48 ft./s. (Magn. ×100.)

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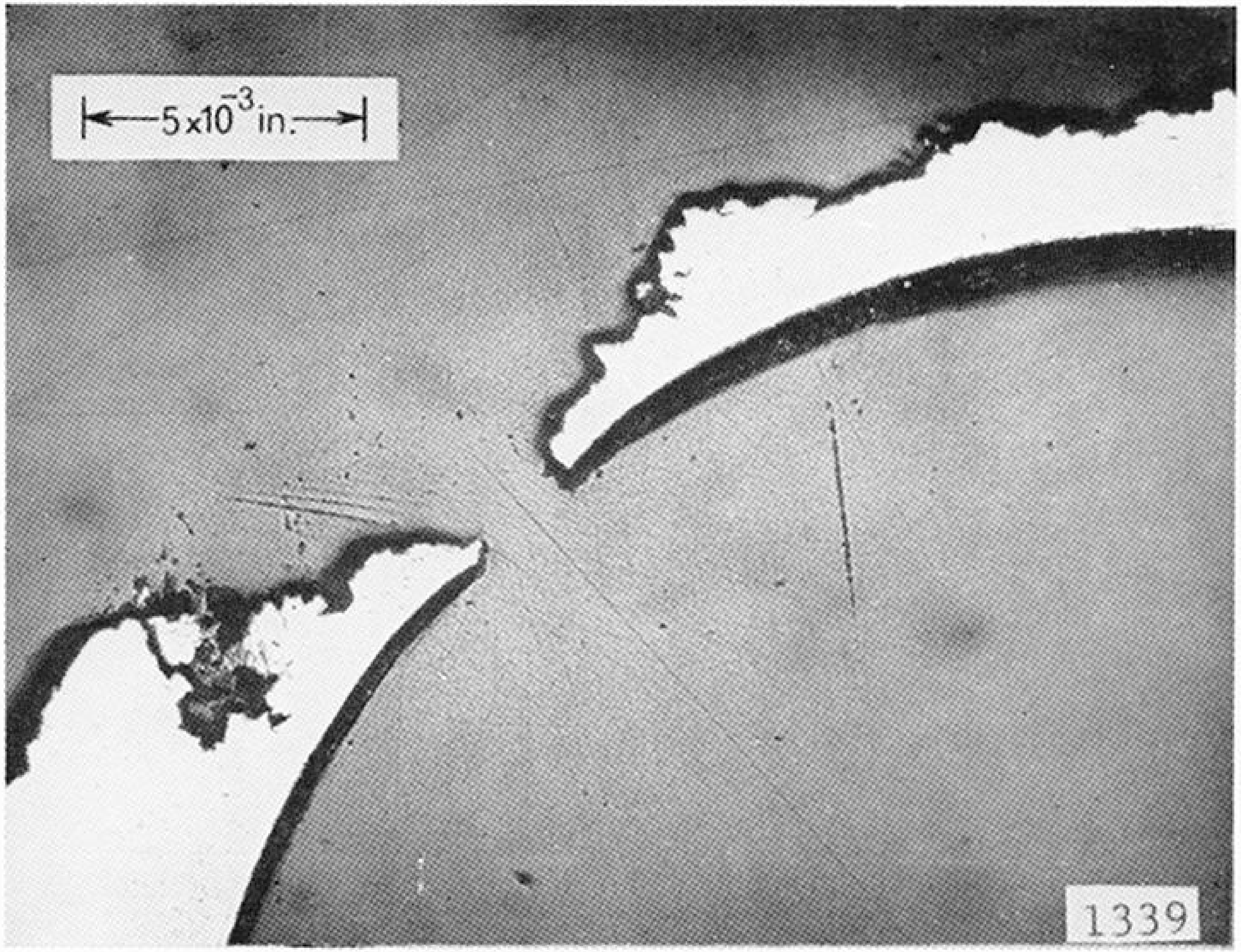

IGURE 8. Metallographic cross section through stainless steel pin specimen wall. (Magn. × 40.)