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EFFECTS OF EXTERNAL LOAD ON CAVITATION DAMAGE

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by

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ABSTRACT

Cavitation damage rates in an ultrasonic cavitation field upon specimens subjected to an externally applied stress are reported. Brass, bronze, aluminum, magnesium, copper, stainless steel and carbon steel were tested in cold water under tensile and compressive stresses of 3/4 of their yield strength, and in one case at twice that value. Damage rates under stress were compared with those for identical specimens under zero load. Generally it was found that compression tends to reduce damage during the constant damage rate portion of the test, while tension increases it. The same trends were found for the very early part of the test. However, the magnitude, and in some cases the direction of the trend, differes for different materials.

Measurements were also made of the effect of a given cavitation volume loss upon the yield and tensile strength of the specimens. In general it was found that the effect is much greater than that which would be predicted on the basis of an exactly uniform damage distribution (mean depth of penetration) across the specimen.

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I. INTRODUCTION

Much effort has been expended for many years to measure the resistance of materials to cavitation erosion, and to relate this resistance to the easily measurable, standard properties of the materials. It is generally recognized that cavitation-erosion in most cases is the result of highly transient and intense mechanical loading on the material combined with corrosion. Acting together in a real case, it is generally true that the combined results of corrosion and cavitation greatly exceed their summed results when acting separately. However, mechanical attack represents the major portion in most cases, and certainly this is true with material-fluid combinations not particularly sensitive to corrosion. It is the purpose of this paper to consider only the mechanical aspects of cavitation damage.

Numerous attemps have been, and are being made, to relate cavitation damage rates in a particular form of cavitation test to the conventional mechanical properties of the materials, considering only those cases where corrosion effects are relatively unimportant. Since the mechanical properties are to some extent functions of each other, it is not surprising that at least a rough correlation can be found in terms of many of these. From our own work[1] we have come to the conclusion that the statistically best results are obtained in the form of an expression as:

$$(\text{Volume Loss Rate})^{-1} \propto C_o + C_1(\text{U. R.}) + C_2(\text{S. E.})$$

where C_o, C_1, and C_2 are constants, $C_1 \gg C_2$,
U. R. = Ultimate Resilience (Failure energy for brittle fracture), and S. E. = Strain Energy to Failure (Failure energy for ductile fracture). Using this equation for a typical set of vibratory facility cavitation data, with the constant fitted for that set, the percent standard deviation is of the order of 40%. Other simple mechanical property correlations are less precise. Nevertheless, there are

numerous individual materials which deviate widely from such best fit curves (factors ~10 are possible). One of the reasons for such large deviations may be the varying state of surface stress that exists prior to attack in different materials and applications where cavitation damage is a factor.

The local stress pattern existing in a material surface at the instant of loading from a nearby cavitation bubble collapse is the resultant of the superposition of the stresses existing in the surface prior to the cavitation attack upon those induced by the attack. The stress pattern existing prior to the attack can be a resultant of superposition of stresses due to applied loads, such as for example centrifugal stresses in a rotating impeller, upon "built-in" stresses due to cold work caused by fabrication techniques, heat treatment, or to the effects of the previous cavitation attack itself.

Micro-material failure of the surface of a cavitated specimen depends upon the magnitude of the combined stresses which are applied. If these are sufficiently great, a fairly symmetrical crater will be formed at the instant of bubble collapse (Fig. 1). If not, minor deformations may occur which will, if repeated a sufficient number of times, result in an eventual fatigue failure of the surface on perhaps a larger scale. In any case, according to the usually accepted maximum shear failure theory for relatively ductile materials, surface failure is governed by the greatest absolute difference between normal stresses, i.e., $|\sigma_1 - \sigma_2|$, $|\sigma_2 - \sigma_3|$, or $|\sigma_3 - \sigma_1|$. When this difference is maximum, shear is also maximum. However, these normal stresses are each a resultant of the superposition of whatever stress magnitudes may have existed in the material prior to the bubble implosion upon those due to the bubble implosion. Fig. 2 shows an idealized example of this situation. The region around an individual crater includes zones of both tensile and compressive loading. Assuming that the load due to the bubble implosion is primarily normal to the surface and compressive, the likelihood of failure if failure is the result of excessive tensile stress normal to the surface (region of crater rim, e.g.) will be increased by imposition of a uniaxial compressive stress parallel to the surface (thus reducing the tensile stress component parallel to the surface), and vice versa. Thus, an important byproduct of a study of effects upon cavitation damage of prestressing is additional basic knowledge upon the nature of the actual cavitation failure mechanism.

II. PREVIOUS WORK

The first work known to the authors on the relationships between applied prestress and cavitation damage was accomplished in this laboratory several years ago [2,3] using mercury in a cavitating venturi. AISI type 304 stainless steel ribbons were held under varying degrees of tension (up to a substantial portion of their ultimate stress) across the venturi with their broad faces parallel to the stream. It was found that cavitation damage rates increased under tension by about 8%; compression was impossible due to the nature of the specimens. It was also observed that the ultimate strength of the specimens was decreased by a given cavitation volume loss to a greater extent when the damage had been incurred under applied load than otherwise. The yield strength was also affected in this way for relatively small tensions, though the effect of large tensions was the reverse (i.e., the yield strength after test was increased when the damage was inflicted on a stressed specimen), probably because of the work-hardening caused by the larger pre-tensions. These results suggest that deeper micro-cracks may penetrate the material below the nominal depth of the cavitation damage when this damage occurs under substantial pre-tension.

Shalnev, et. al.[4] in Russia later studied the effects of prestress on cavitation damage using an aluminum wrought alloy (similar in composition and mechanical properties to Type 3003-0 aluminum

as the test material). His tests were conducted using a vibratory damage facility, and positioning the stressed specimens in close proximity to the tip of the cavitating horn. Only tensile stresses were investigated. He found that damage rates were almost doubled for relatively moderate tensile stresses (~2000 psi). Greater stresses (to ~6000 psi) had little additional effect. (The yield strength of his material was 10,700 psi).

III. EXPERIMENTAL APPROACH FOR PRESENT STUDY

A. Test Facility and Specimens

Our present study, which is the primary subject of this paper, uses an arrangement much like that reported by Shalnev et. al.[4], except that provision is made for both compression and tensile prestress. Fig. 3 is a schematic and Fig. 4 photographs of the facility and one of the specimens. The flat specimen is held close (24 mils spacing used in all present tests) and parallel to the lower face of the vibrating horn (nominal 20 kHz, 2 mil unit) by a hydraulic ram capable of applying either tensile or compressive loads sufficient to stress even relatively strong materials (such as 304 stainless steel) to approximately its ultimate stress. The entire arrangement is contained in an open tank wherein the fluid level is maintained somewhat above (1 1/2 inches) the tip of the vibrating horn. We have made cavitation damage tests of unstressed specimens in this way before, and found the results to be highly reproducible with damage rates only slightly less than those obtained in a standard vibratory test[5, 6]. Since damage rate depends strongly on the clearance between specimen and horn tip (in its static position) this dimension was maintained constant. Table I shows the pertinent test conditions.

TABLE I - FACILITY TEST CONDITIONS

Frequency of Horn	20 kHz
Horn Amplitude	2 mils
Water Temperature	$23^{o}C$
Type of Water	Distilled
Water pH	~7.4
Gas Content of Water	Saturated
Prestress	Compressive, zero or tensile as specified.

As shown in Fig. 4-b the specimens are designed with end segments of adequate strength to allow post-test breaking in a tensile machine. It is thus possible to determine the change in both yield and ultimate strength of the specimens as a result of a measured cavitation-induced MDP* as a function of the prestress condition under which it was incurred.

B. Scope of Tests

The materials were chosen to represent as broad a range of properties and structures as possible. Those tested include O. F. H. C. copper, 3003-0 aluminum, SAE 660 bearing bronze, 65/35 brass, 304 stainless steel, 1020 carbon steel, and tooling plate magnesium alloy. However, most of the effort was concentrated on the aluminum alloy (selected to be similar to that used by Shalnev et. al.[4]), the brass, and the copper. The effect of direction of rolling as compared to prestress direction was tested for the aluminum alloy, and the copper. The pertinent mechanical properties of these materials are listed in Table II. All materials were tested under compressive and tensile applied stress,

*MDP = Mean Depth of Penetration = Volume Loss/Damaged Area.

and also under zero applied stress. With the exception of a final test with copper, where 1.5 yield strength was used, the applied stress was 3/4 of the yield stress of the material. Stress-strain curves to failure were generated for selected cavitated specimens on a tensile machine as well as on two non-cavitated "control" specimens of these types. At least two specimens were used to establish all the cavitation damage data point (which in each case are the numerical average of the weight losses at that test duration), and in some cases nine specimens were used. While there were 30 separate test conditions (considering the stress conditions separately) a total of 138 specimens were used in this averaging process. Reported damage rates are based upon the slope of the best straight line through the data points in that portion of the weight loss versus duration curve where the slope is uniform. Fig. 5 for aluminum is fairly typical for this test arrangement. Weight loss rate increased relatively rapidly, depending on the material, from the initiation of the test, and achieved a constant value which is maintained throughout the remaining duration of the test. No evidence was found with any material of an "incubation period" where the weight loss was zero (within the precision of the balance) even though the initial time interval was short (from 3 minutes for aluminum to 30 minutes for the steels). All the test curves and other detailed data may be found in ref. 6.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. General Cavitation Damage Results

The most apparent result of the prestressed cavitation damage tests, as well as of the effects of cavitation damage accrued under these conditions upon the stress-strain curve for the specimens, is that the effects differ widely in both direction and magnitude, depending upon the specific material. Even for this simple test which uses only uniaxial tension and compression, there is an overall trend, however, indicating increased damage rate for materials cavitated under pre-tensile loads and a damage decrease for pre-compression. There are ten separate test conditions (differing in material, stress as a portion of yield stress, or specimen orientation with respect to rolling direction). For each of these, tests were made to compare damage rates under pre-tension, pre-compression and zero prestress. The averaged and extreme results for cavitation damage rates are shown in Table III. In some cases the more dramatic effects were encountered in the early portion of the curves, as shown in Table III-B.

The complete cavitation damage results are shown in Table IV for both linear rate and early portion. Since the results differ widely for the different materials it is necessary to discuss them individually. However, Tables III and IV show immediately three significant points:

1. The maximum effects observed on the linear damage rate do not exceed $\pm$ 20%, while in the initial test periods the effects are much larger (up to 56%). The occurance of larger effects in the initial period is consistent with much cavitation damage test experience wherein the behavior of even apparently similar specimens under similar test conditions varies much more widely in the early part of a test than later after a steady rate has been achieved.

2. The average effect during the linear portion of the test is that compression slightly reduces damage, while tension increases it to somewhat greater extent. In the early ("incubation") period the mean effects are in the same direction.

3. The largest effect upon the linear damage rate occurred with the only hexagonal close packed (HCP) material tested (magnesium alloy), whereas the largest effect upon early damage rates with the parallel rolling direction was for the only body centered cubic (BCC) material (carbon steel). The remaining materials were face centered cubic (PCC). It is impossible to predict without additional tests on other HCP and BCC materials whether or not this structural characteristic is important.

B. <u>Cavitation Damage Results for Different Materials</u>

L. Brass (65-35). This showed the greatest increase of damage of any of the materials due to tension: 16.9% in constant rate portion and 25% in early portion (first 15 minutes). The effect of compression was large in the initial 15 minutes, reducing weight loss by about 25%, whereas its effect on the linear rate was only to reduce weight loss by about 1.8%.

2. Aluminum (3003-0). This aluminum alloy was selected to be similar to that used by Shal'nev et. al.[4]. However, some difference in alloys apparently exists since the yield strength of our material was about 7000 psi while that of Shal'nev was 10, 700 psi. Direct comparison of results cannot then be expected. However, Shal'nev's tests indicated a considerably greater effect, even at small pre-tension values, than did ours.* Our aluminum tests encompassed not only the effect of prestress, but also that of the direction of rolling in the fabrication of the specimen stock. We investigated this effect for copper also, but in all other cases the direction of rolling was parallel to the prestress.

a. Aluminum (Parallel Rolling)

The aluminum test with parallel rolling direction showed an approximate 14% spread between compression and tension, about equally spaced about the zero prestress condition. This is unusual in that the reduced damage with compression is generally greater than the increase with tension. The effects early in the test show an increased damage rate for both compression and tension.

b. Aluminum (Perpendicular Rolling)

For the rolling direction perpendicular to prestress, both compression and tension produced more damage than the zero stress condition (4 and 10% respectively). In the early portion of the test, both also produced more damage than zero force (56% compression, 23% tension). The effect of rolling direction is probably due to the additional built-in stresses due to rolling and thus the different resultant stresses prior to cavitation attack. Presumably the stress pattern in the specimens rolled perpendicular to prestress is two-dimensional, while that of the parallel-rolled specimens is substantially one-dimensional. The damage is greater for all cases for the perpendicular tests.

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*He showed a maximum effect of 120% change for 2800 psi tension after 8 minutes and then a decreasing effect.

for the perpendicular tests.

3. SAE 660 Bronze. A relatively slight effect of prestress was noted in the linear portion of the test (Table IV), although the ordering was typical (most damage for tension and least for compression). Larger effects were observed in the early portion of the test where compression and tension both reduced damage by about 16%.

4. OFHC Copper. Copper was the only "pure" metal included in the study. As with the aluminum alloy, the effects of rolling direction were investigated as was also the effect of increasing the prestress to 1.5 times yield strength, versus 0.75 used in all other tests.

The effect of prestress magnitude or direction on the linear damage rate is relatively small, as is that of the direction of rolling. In all the comparative tests with copper the largest variation from the zero force condition was only 3.1%. Thus, while the copper results are essentially negative, general precision and reproducibility of the data is shown in that the greatest discrepancy from the control case is only about 3% in spite of the large variations of prestress and rolling direction.

Somewhat larger effects were noted in the earlier portion of the test (typical for most materials*). In both the parallel and perpendicular direction standard load test, tension increased the damage rate about 9% and compression about 18%. Comparison of the early portion (first 15 minutes) of the tests under 1.5 yield strength with those under 0.75 yield, shows that the increased load decreases damage in this portion by 34% for the compressive test and about 26% for the tensile case. In both cases the zero force test is approximately intermediate. The explanation for the decrease in damage for increased applied load, either tensile or compressive, may be that the permanent deformation involved in stressing the specimens beyond yield has

*Shal'nev [4] noted similar results (previous foot-note).

induced sufficient work-hardening in the surface to more than offset the effect of the additional prestress.

5. 304 Stainless Steel. Type 304 Stainless steel was unique in that tension decreased the linear damage rate (2.4%). Compression slightly increased this rate (1.4%) which was also unusual, though not unique. Much larger effects were encountered in the early portion of the test (to 2 hours), where tension decreased damage by 53.4% and compression decreased it 16%. The trend toward decreasing damage under tensile load was not consistent with the earlier tests conducted in this laboratory[2, 3] with this material in a cavitating mercury venturi.

6. Carbon Steel (1020). Carbon steel was chosen for test because of its body centered cubic (BCC) structure, and its wide-spread use. All materials discussed so far are of face centered cubic structure (FCC), and magnesium (to be discussed) is of hexagonal close packed (HCP) structure. With carbon steel the effect of prestress of <u>either</u> direction was a small increase in the linear damage rate (3.3 and 4.5%). Again the effects in the early portion of the test were much greater, since the tensile load decreased the damage rate 18% while the compression decreased it by 52% (the largest effect noted in any of the tests conducted with the stress applied parallel to the rolling direction). In these relatively short tests (5 hours) only very slight corrosion was noted, although its effect may have been important.

7. Magnesium Tooling Plate (HCP structure). This material exhibited the largest difference of all between linear damage rates in compression and in tension (-13.8 and +13.0% respectively giving 26.8% spread). Again the effects in the earlier part of the test were greater: +7% for tension and -48% for compression. The magnesium curve is included (Fig. 6) along with that for the perpendicular direction aluminum (Fig. 5) to show examples of curves with both a typical and a large effect due to prestress.

C. Effect of Cavitation Damage on Mechanical Properties

Earlier tests in this laboratory[2, 3] had shown that the gross weakening of a specimen due to a given volume loss in cavitation was affected by the applied stress under which the damage had occurred. To further investigate this possibility and to obtain information on the effect of a given MDP (mean depth of penetration) in weakening a cavitated structural member, a number of the copper and aluminum specimens from the present tests were subjected to a stress-strain breaking test on a standard tensile machine. Before the breaking test, however, they were subjected to additional cavitation damage on both sides for symmetry and to obtain as large a proportionate reduction in cross-section area as possible. An area reduction of 9-10% was attained in all cases to achieve statistically meaningful results. The stronger materials were not included in this portion due to their excessive test times.

After additional cavitation damage had been accrued, the widths of the specimens were reduced in a milling operation so that the dammaged region covered most of the remaining neck of the specimen. Fig. 7 shows a specimen prepared in this fashion. The full details of the procedure and data reduction are given in ref. 6.

The results are presented in the form of a ratio of percent change of tensile or yield strength to percent change in cross-sectional area as computed directly from MDP (Table V). If the material was removed by cavitation or was in a layer of uniform thickness with no penetration below the nominal depth of such a layer, then a given percent reduction in the area computed on this basis should produce the same percent reduction in the strength properties. If the ratio is greater than unity, the effect of cavitation damage on the strength of the damaged member is proportionately greater than the nominal area reduction. If the ratio is negative, the cavitation damage has actually strengthened the member, presumably through cold work effects. This was actually observed in two cases. However, typical results show ratios somewhat greater than unity, the largest being 2.15 for the yield strength of copper with zero load.

In the previously reported tests from this laboratory with 304 stainless steel in mercury[2, 3] it was found that a given MDP accrued under tension had a greater weakening effect than if accrued under zero load. Examination of table V shows that this is generally not the case in the present tests where the largest effects are found for zero load in most cases. Also there is little difference between the effects of tension and compression in the present tests.

In general, it appears that countering machanisms are involved. Clearly the non-uniform distribution of the cavitation volume removal should weaken the specimen by a larger proportion than the nominal area reduction. If in addition microcracks penetrate below the cavitation pits, as was observed in this investigation[6], the strength reduction should be increased. However, at the same time, the cavitation itself work-hardens the material at least near the surface, and, depending upon the material, may more than counter the effect of the uneven distribution in volume loss.

The effect of prestress on residual strength of specimens is also difficult to predict. It would be expected that a substantial tensile load would increase the depth of penetration of microcracks below the pitted surface, whereas compression might inhibit this penetration. In addition, the prestress itself may result in some work-hardening of the material, especially in combination with the cavitation attack. The present results, however, show no clear trend.

V. CONCLUSIONS

The tests reported using a wide variety of materials have shown that the effects of external applied stress upon cavitation damage rates can be quite substantial, particularly (though not exclusively) in the early part of the test. Since these results were achieved with only uni-axial application of external load, it is quite likely that future tests with two or three dimensional stress patterns will show in some cases even more dramatic results. While there is very little work on the relationships between cavitation-induced failure and stress, there is a considerable literature on the relations between residual stress and component failure in general[7, e.g.].

In addition, measurements have been made of the effects upon the gross strength properties (yield and tensile) of specimens previously subjected to cavitation to determine the proportionate effect of a given reduction of cross-sectional area by cavitation as computed for nominal penetration depth (mean depth of penetration). These results allow at least an engineering estimate of this effect for different materials and for damage accrued under different conditions of prestress, as would of course apply in most operating machines.

ACKNOWLEDGEMENTS

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TABLE II - MATERIALS PROPERTIES

Material / Item	Hardness DPH_1 kg load	Density gm/cc	Elongation %	Yield Strength	Tensile Strength	Modulus of Elasticity
Brass (65/35)	146.1	8.47	39.3	48,879	60,473	15.7×10^6
1020 Carbon Steel	227	7.70	25.9	89,725	96,515	31×10^6
304 Stainless Steel	315	7.85	16.75	40,990	99,419	29×10^6
SAE 660 Bronze ASTM B 144	174.3	8.93	17.3	17,545	22,488	6×10^6
Magnesium Tooling Plate	88.5	1.77	25.5	24,120	39,225	6.5×10^6
Alum. 3003-0	51.2	2.74	54.1	6,775	15,864	9×10^6
OFHC Copper (7/8 hard.)	96.8	8.94	54.3	28,200	33,345	$16. \times 10^6$

TABLE III - AVERAGE AND EXTREME DAMAGE RATES

A. Rates Measured in Linear Portion of Curve

	Percent Change Compression *	Percent Change Tension **
Maximum Positive	+4.5	+16.9
Maximum Negative	-13.8	-2.4
Algebraic Average	-1.5	+5.8

B. Initial Rate Effects

	Percent Change Compression *	Percent Change Tension * *
Maximum Positive	+56.4	+53.7
Maximum Negative	-51.8	-53.4
Algebraic Average	-4.2	+1.16

$$* \quad \frac{\text{Compressive Weight Loss} - \text{Zero Load Weight Loss}}{\text{Zero Load Weight Loss}} \times 100$$

** Comparable to definition above for tensile weight loss.

TABLE IV - SUMMATION OF DAMAGE RATES

Material	Structure	Damage Rate (mg/min) Zero Force	Damage Rate (mg/min) Compression	Damage Rate (mg/min) Tension	Linear Rates $\Delta C\% = \frac{CR-ZFR}{ZFR}$ (x 100)	Linear Rates $\Delta T\% = \frac{TR-ZFR}{ZFR}$ (x 100)	Initial Rates $\Delta C\% = \frac{CR-ZFR}{ZFR}$ (x 100)	Initial Rates $\Delta T\% = \frac{TR-ZFR}{ZFR}$ (x 100)
Parallel Rolling Direction								
Brass (65/35)	FCC	0.4099	0.4026	0.4795	-1.78	16.94	+5.89	+53.7
Aluminum 3003-0	FCC	2.369	2.1845	2.518	-7.79	6.29	+7.67	+14.06
SAE 660 Bronze	FCC	0.3754	0.3733	0.3898	-0.56	3.84	-16.59	-16.09
OFHC Copper	FCC	1.708	1.735	1.761	1.58	3.10	+17.63	+9.32
304 Stainless Steel	FCC	0.07408	0.07510	0.07229	1.38	-2.42	-15.85	-53.4
1020 Carbon Steel	BCC	0.1772	0.1843	0.1831	4.46	3.33	-51.80	-18.0
Magnesium Tooling Plate	HCP	0.2186	0.1885	0.2469	-13.77	12.95	-47.8	+6.58
Increased Force - 150% Y.S.***								
OFHC Copper	FCC	1.708	1.714	1.745	0.35	2.17	-16.2	-16.72
Perpendicular Rolling Direction								
Aluminum 3003-0	FCC	2.369	2.458	2.614	4.19	10.34	+56.40	+23.41
OFHC Copper	FCC	1.708	1.664	1.740	-2.58	1.87	+18.77	+8.30
				Av =	-1.42	5.84	-4.24	+1.76

* $\frac{\text{Compression - Zero Force}}{\text{Compression}} \times 100$

** $\frac{\text{Tension - Zero Force}}{\text{Compression}} \times 100$

***All others 75% Y.S.

TABLE V - STRESS-STRAIN TEST RESULTS

MATERIAL	Δ% Yield Strength / Δ% Area	Δ% Tensile Strength / Δ% Area
Copper (Parallel Rolling Direction)		
Zero Force	2.15	1.56
Tension	1.74	1.45
Compression	1.85	1.50
Aluminum (Parallel Rolling Direction)		
Zero Force	1.417	1.164
Tension	-0.696	1.10
Compression	+0.480	1.10
Aluminum (Perpendicular Rolling Direction)		
Zero Force	0.455	1.379
Tension	-1.182	1.353
Compression	1.155	1.65

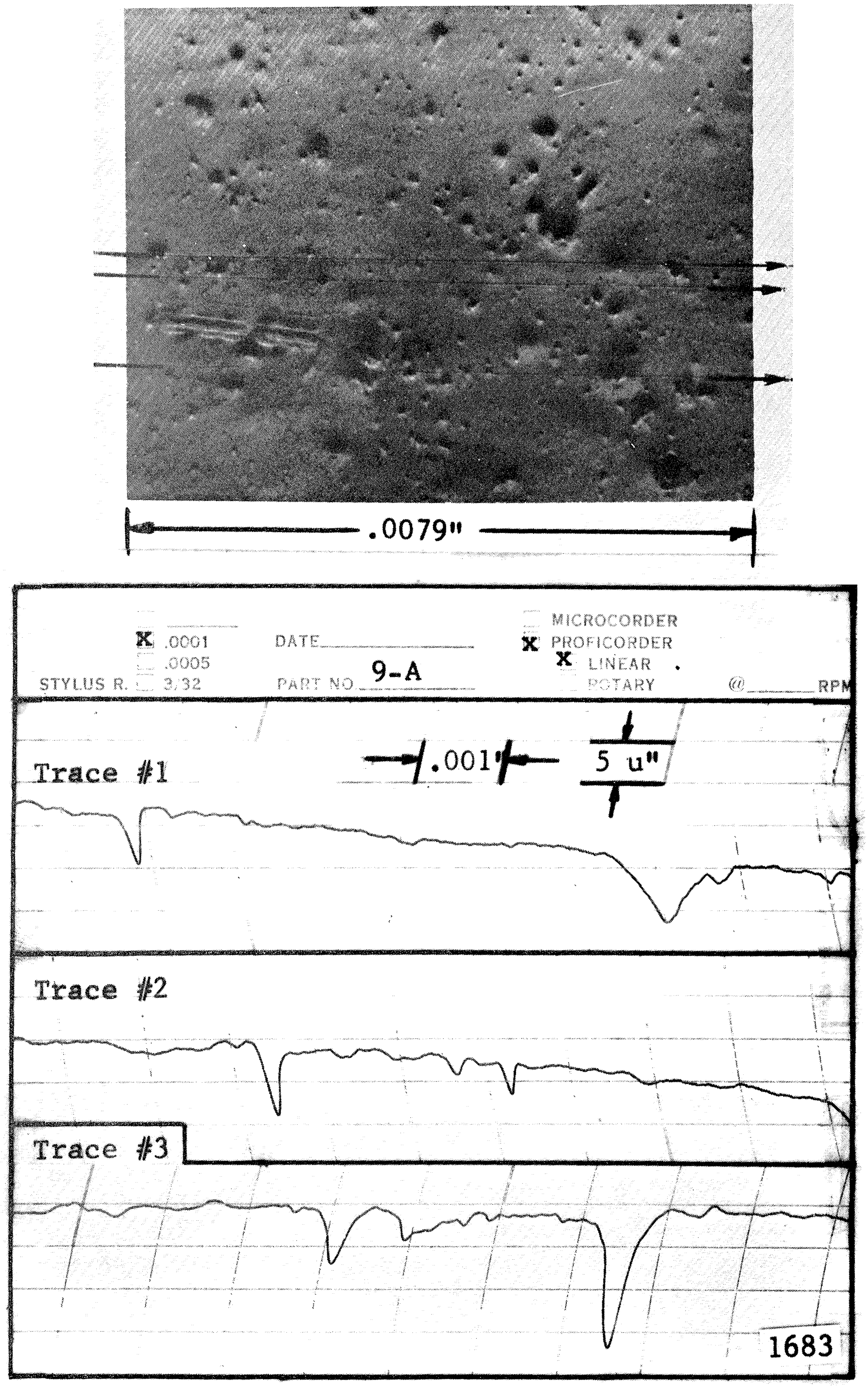
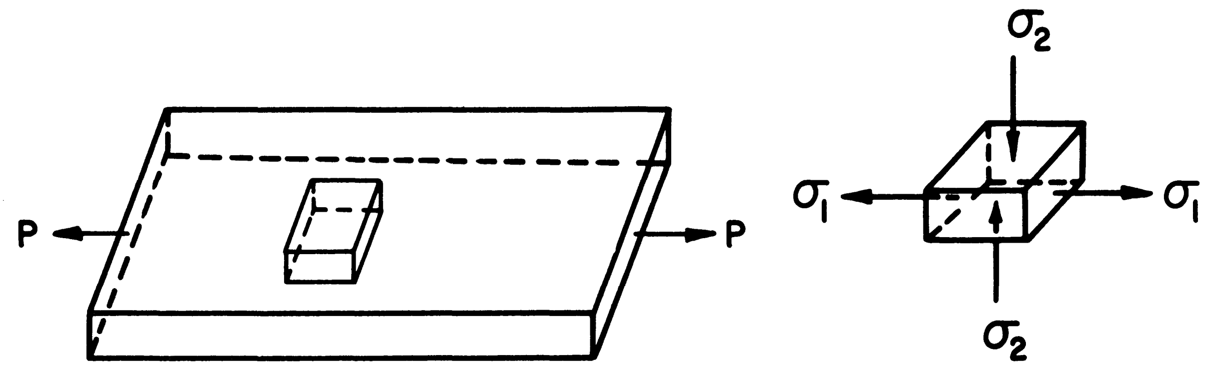


Fig. 1. Photomicrograph and Proficorder Traces of Tantulum-Tungsten (Ta-IOW) Alloy Cavitated in Mercury Venturi (10 hrs.)

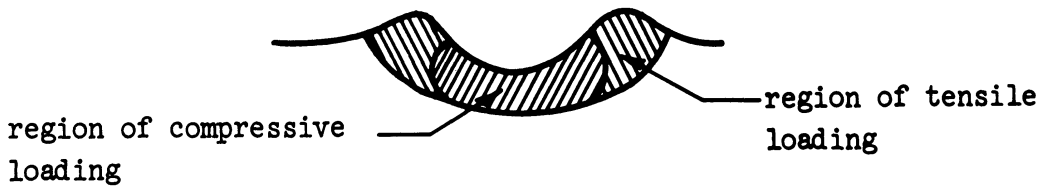


$\sigma_{failure} = |\sigma_1 - \sigma_2| < |\sigma_1|$ when σ_2 is tensile

σ_1 = tensile stress due to applied load, P

σ_2 = Normal stress due to hubble implosions

(a)



(b)

1601

Fig. 2. Stress Distribution for Typical Cavitation Pit

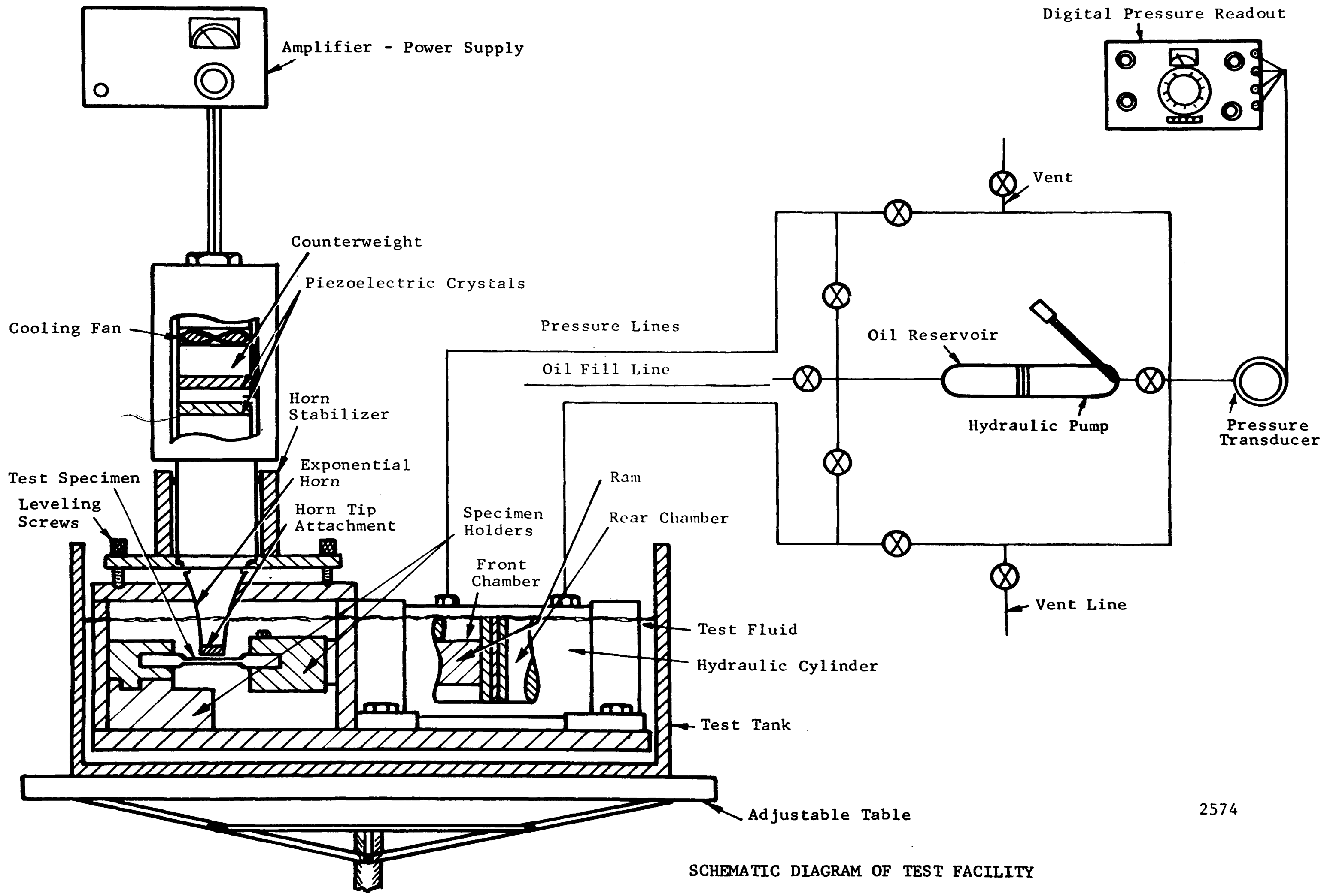


Fig. 3. Vibratory Cavitation Damage Facility for Close Proximity Test of Pre-Stressed Specimen -- Schematic Diagram

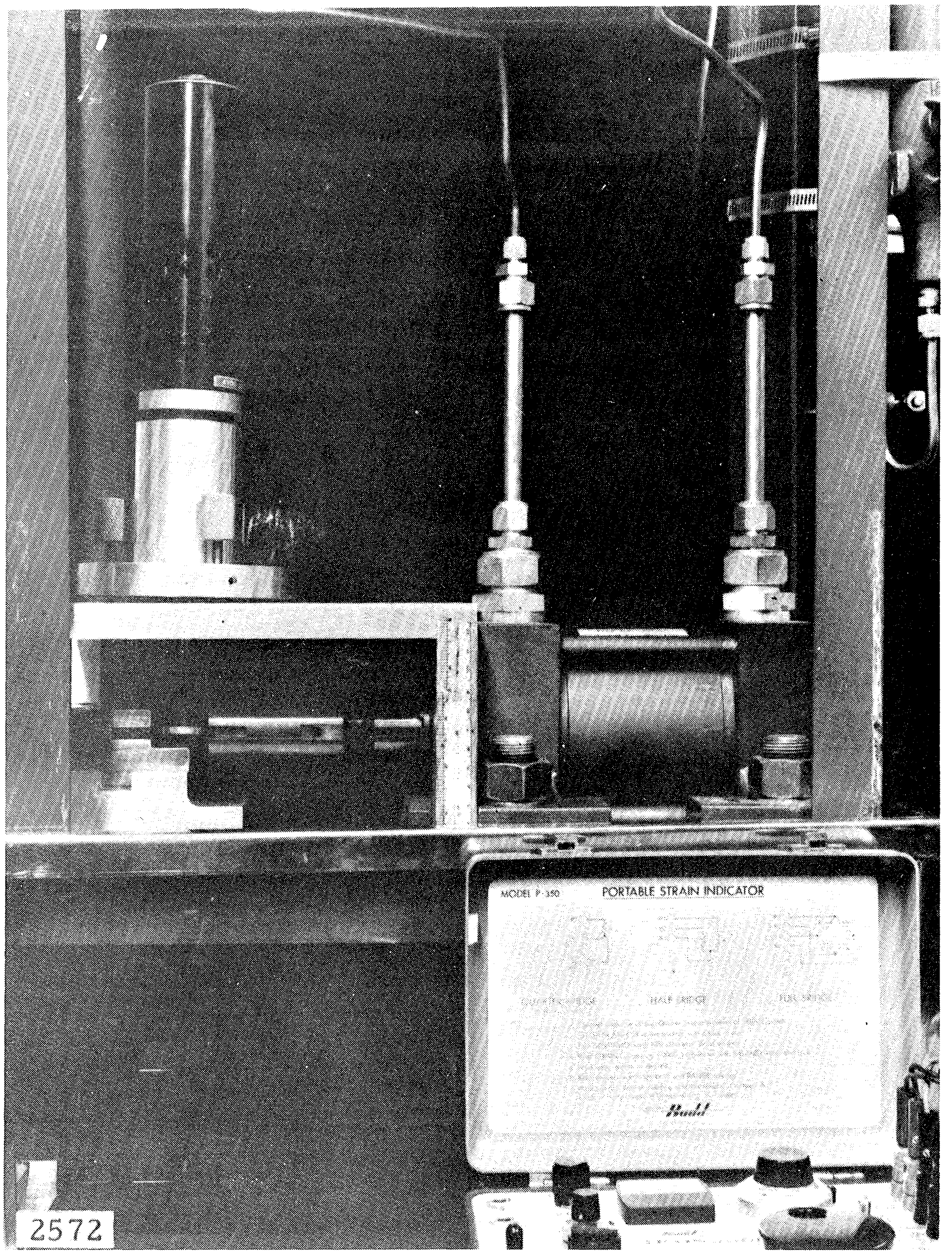


Fig. 4. a. Photograph of Vibratory Cavitation Damage Facility for Close Proximity Test of Pre-Stressed Specimens

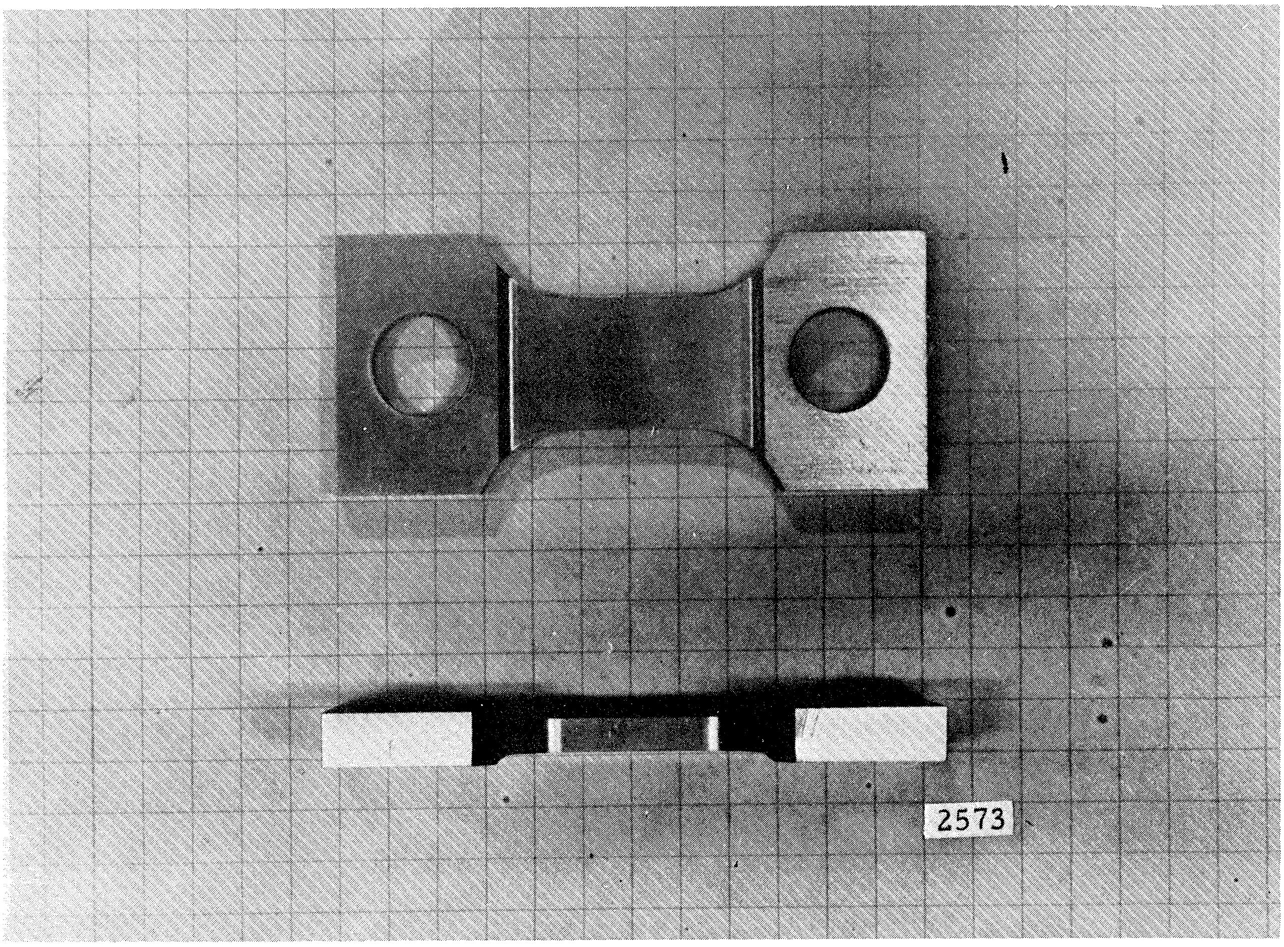


Fig. 4. b. Pre-stress Close Proximity Specimen

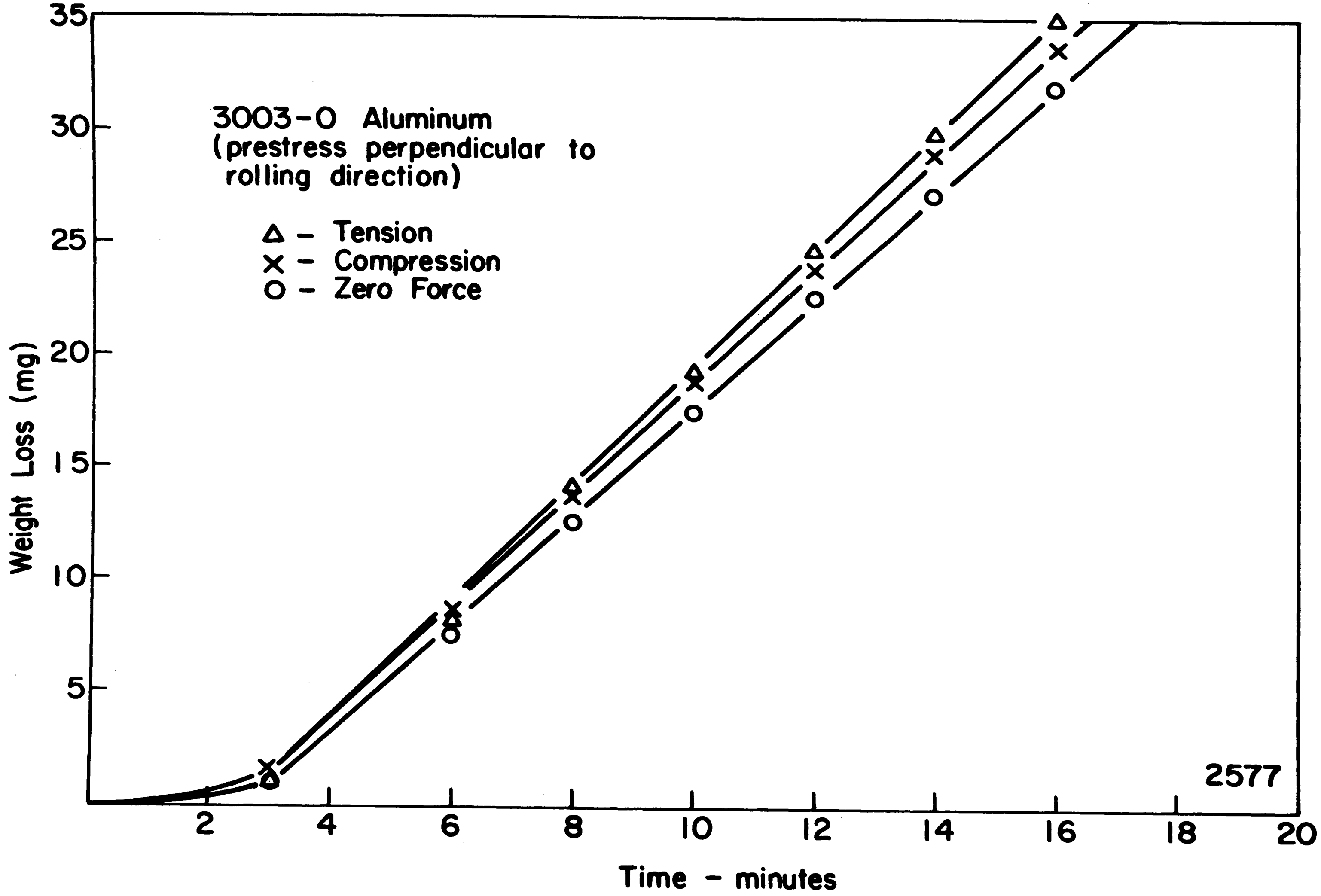


Fig. 5. Weight Loss versus Duration for Al 3003-0
(Perpendicular Rolling Direction)

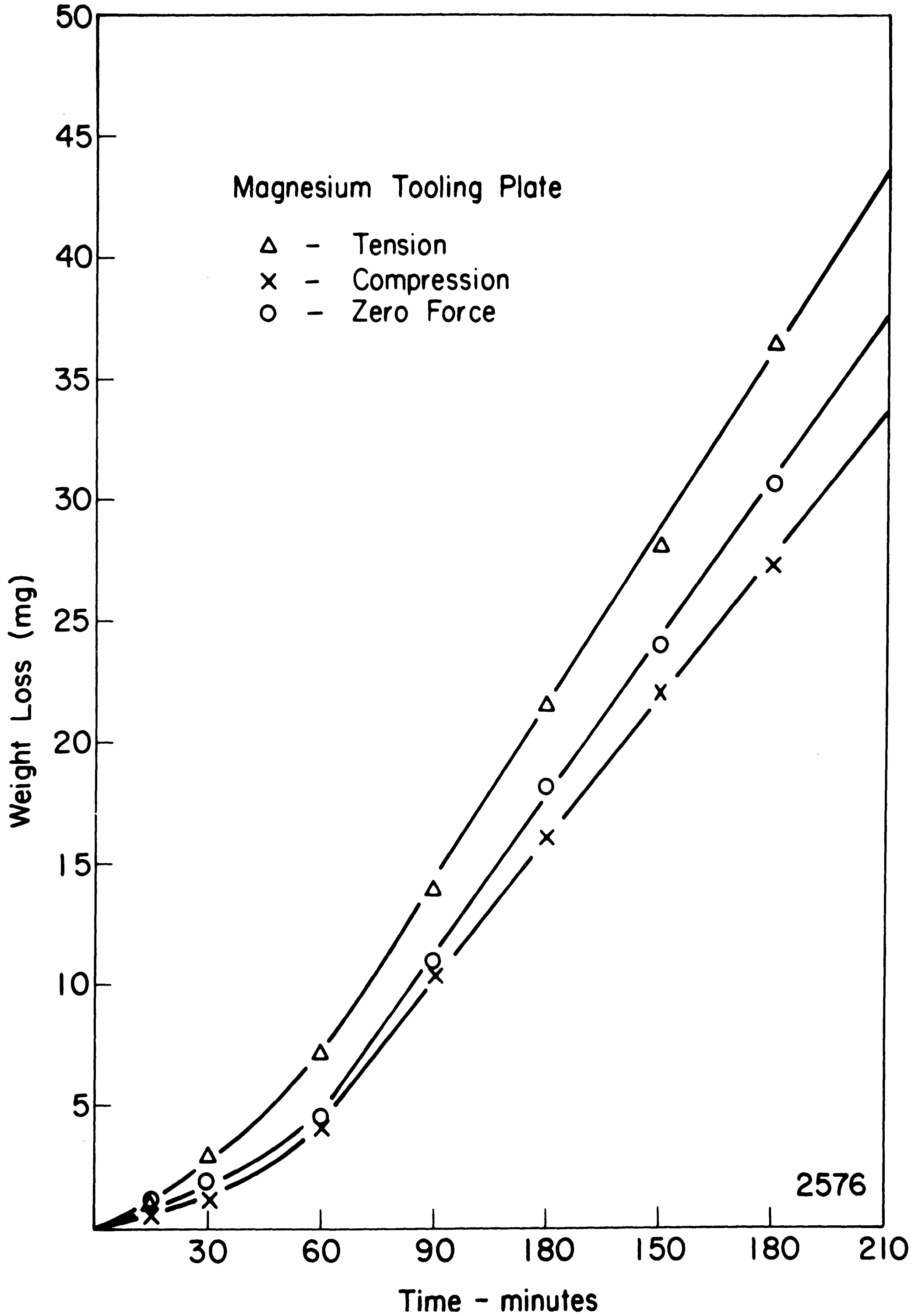


Fig. 6. Weight Loss versus Duration for Magnesium Tooling Plate

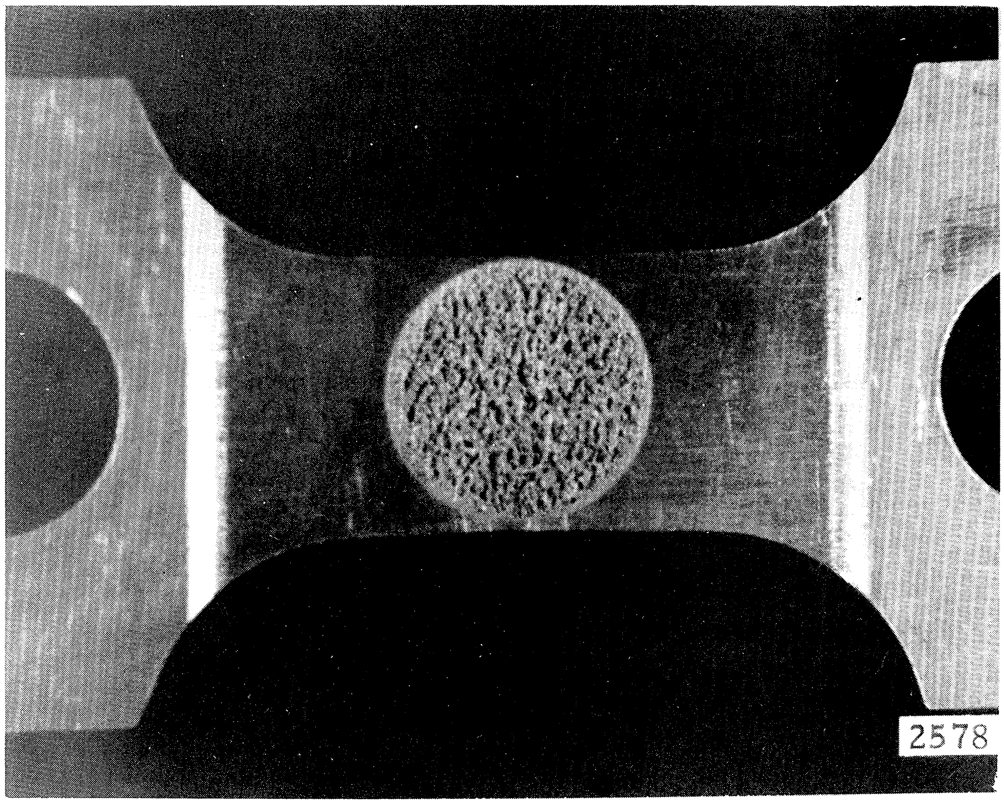


Fig. 7. Photograph of Damaged Specimen for Stress-Strain Test