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# CORROSION FATIGUE OF STRUCTURAL METALS IN MINE SHAFT WATERS

G. J. BIEFER

PHYSICAL METALLURGY DIVISION

JULY 1965

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# CORROSION FATIGUE OF STRUCTURAL METALS IN MINE SHAFT WATERS

by

G. J. Biefer*

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## ABSTRACT

Fatigue and corrosion fatigue measurements were carried out on five commercially available metals - four steels and an aluminum alloy - which are used as structural materials in mine shaft conveyances. In the corrosion fatigue measurements, drain waters collected in the shafts of three different Canadian mines were used as corrodents. The mine waters had been selected on the basis of their relatively large differences in acidity and/or composition.

It was found that the corrosion fatigue strengths of the four steels were similar despite their differences in tensile properties. The type of water used in the tests had little or no effect on the results. However, mild steel showed the highest and most consistent values of the damage ratio (ratio between the corrosion fatigue and the plain fatigue strengths at $10^7$ cycles).

The corrosion fatigue behaviour of the aluminum alloy (ASTM Type 6061-T6) was found to differ markedly in the three mine waters. A high damage ratio was shown in a mine water in which the corrosion rate was low and the attack uniform. Much lower damage ratios were shown in mine waters which produced localized corrosion attack.

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Direction des mines

Rapport de recherches R 167

# FATIGUE-CORROSION DES MÉTAUX DE STRUCTURE DANS LES EAUX DES PUITS DE MINE

par

G.J. Biefer*

## RÉSUMÉ

L'auteur a mesuré la fatigue et la fatigue-corrosion dans le cas de cinq métaux que l'on peut se procurer dans le commerce - quatre aciers et un alliage d'aluminium - et qui sont utilisés dans la fabrication des véhicules employés dans les puits de mines. Pour les mesures de la fatigue-corrosion, l'auteur a utilisé comme agent de corrosion des eaux d'égout provenant de trois mines canadiennes différentes. On a choisi les eaux en tenant compte de leurs différences assez marquées en acidité et/ou dans leur composition.

L'auteur a trouvé que la résistance à la fatigue-corrosion est semblable pour les quatre aciers, en dépit de leurs différences de résistance à la traction. La nature de l'eau utilisée dans les épreuves n'a eu que peu ou point d'effet sur les résultats. Cependant, l'acier doux est celui qui donne les valeurs les plus élevées et les plus uniformes en ce qui a trait au rapport de dommage (rapport entre la résistance à la fatigue-corrosion et la résistance à la fatigue ordinaire pour $10^7$ cycles).

Le comportement de l'alliage d'aluminium (ASTM type 6061-T6) dans le cas de la fatigue-corrosion est très différent pour les trois genres d'eau utilisés. L'auteur a trouvé un rapport de dommage élevé pour une eau dont la vitesse de corrosion est lente et l'attaque uniforme. Les rapports de dommage sont beaucoup plus bas dans les eaux de mine qui produisent des attaques de corrosion localisées.

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## INTRODUCTION

Under normal operating conditions, the load-supporting members of mine shaft conveyances such as skips and cages are subjected to periodic changes in stress as a result of stopping and starting, loading and unloading. At the same time, the conveyances are subject to corrosion, e.g. by waters draining from the surface or from walls of the mine shaft. The combined action of fatigue and corrosion, i.e. corrosion fatigue, is suspected to be a factor in a number of cases where the load-supporting members of conveyances have failed, with damage to equipment, interruption of production, and sometimes loss of life(1,2).

Because very little information is available on the corrosion fatigue resistance of structural metals used in Canadian mines, it was decided to initiate studies in this area. The primary object of the work was to provide basic information which could be used to estimate the resistance to corrosion fatigue of load-bearing members of mine shaft and other comparable conveyances.

## EXPERIMENTAL

### 1. Metals

The following five metals were selected for the corrosion fatigue studies, and were obtained as $\frac{1}{4}$ in. x 48 in. x 120 in. plates through normal commercial channels.

(a) "T-1" Steel - The United States Steel Corporation
(b) "Abrasive-Resistant" Steel - The Steel Company of Canada Limited
(c) Mild Steel (ASTM Grade A-7) -
(d) "Stelcoloy-G" Alloy -
(e) ASTM 6061-T6 (Alcan 65S-T6)* aluminum alloy - Aluminum Company of Canada Limited

* Canadian Standards Association (CSA) HA.4 GS11N T-6.

Compositions and mechanical properties of these metals are listed in Tables 1 and 2.

## 2. Mine Waters

Small specimens of mine shaft water were obtained from thirteen representative Ontario mines for detailed analysis by the Industrial Waters Section, Mines Branch. Three mine waters showing markedly differing combinations of acidity and composition, and hence, presumably, different corrosivity, were then selected for the corrosion fatigue measurements. Larger quantities of each of these waters, from the mines listed below, were obtained for use in the tests.

(a) Levack Nickel Mine (International Nickel Co. of Canada), Levack, Ontario, drip from No. 2 shaft.

(b) Helen Iron Ore Mine (Algoma Ore Properties), Wawa, Ontario, from No. 5 shaft, 1600 ft below collar.

(c) Leitch Gold Mines Ltd., Beardmore, Ontario, water collected in a ring 2863 ft below the surface.

The analyses of the batches of water from these three mines which were used in the tests appear in Table 3.

## 3. Apparatus and Techniques

The corrosion fatigue tests were carried out on a Krouse Reverse-bend Plate Fatigue Testing Machine having a maximum load of 150 lb on the connecting rod, operating at a rate of 1725 cycles/minute. For each specimen, a bent-beam formula was used to calculate the maximum stress encountered in the gauge length during the cycling.

The fatigue specimens were machined so that their $8\frac{1}{2}$ in. lengths lay in the rolling direction, and all flat surfaces were given a fine machine finish. In plain fatigue tests, the specimens were completely coated with lanolin, to prevent atmospheric corrosion attack.

In corrosion fatigue tests, the specimens, after installation in the Krouse tester, were thoroughly degreased using acetone or ethanol. The bottom and sides of the specimen were then coated with lanolin, as was all of the upper surface except a $\frac{1}{2}$ in. wide strip (see Figure 1). At high stresses, where the lanolin flowed over the bare strip because of a rise in specimen temperature during the tests, plasticene dams were constructed at the edges of the bare strip to prevent this flow.

During corrosion fatigue tests, the pertinent mine water was dripped onto the bare strip of metal at a low rate (2-5 drops per minute) by gravity feed from a reservoir containing 2-4 litres, and was found to form an adherent though agitated pool on the rapidly cycling specimens. Specimens showing incomplete wetting on the strip, due to improper cleaning, were discarded. Specimens showing complete wetting almost invariably showed breaks which were partly or completely on the wetted strips. Results obtained with specimens of the aluminum alloy in Helen mine water were abnormal in this regard and will be discussed later.

In the case of the ASTM 6061-T6 aluminum alloy, but not the steels, short-term corrosion tests were carried out. Prior to the tests, the rectangular specimens (Figure 2) were ground to a uniform finish on water-cooled 120 grit silicon carbide paper lubricated with soap. They were then rinsed thoroughly in tap water, degreased in ultrasonically agitated carbon tetrachloride, dried in hot air, then measured with a micrometer and the total exposed area calculated. This was approximately 18 $cm^2$. The specimens were then weighed on an analytical balance with an accuracy of ± 0.1 mg.

The tests were carried out on three identical aluminum alloy specimens simultaneously, each specimen being alternately dipped for 5 min into a pyrex beaker containing 200 ml of one of the mine waters, removed for five seconds, then re-immersed. This process was continued during a total test duration of 24 hr, using a fresh batch of mine water for each test. In all, three tests were carried out in each of the mine waters.

## RESULTS

### 1. Fatigue and Corrosion Fatigue Strengths

In Figures 3-7, the maximum applied stresses (on a linear scale) are plotted against the cycles to failure (on a logarithmic scale) for each of the five metals investigated, thus providing the basis for what are usually called S/N curves. Table 4 lists the plain fatigue and corrosion fatigue strengths at $10^7$ cycles observed in the tests. The highest stresses at which the specimens survived $10^7$ cycles without breaking were used in this table, provided that no breaks occurred at stress levels lower than this value. Table 5 lists the ratios between the corrosion fatigue and fatigue strengths at $10^7$ cycles for the five metals, i.e. their damage ratios.

For the ASTM 6061-T6 aluminum alloy, the results of the corrosion fatigue tests in Helen mine water were unique in two respects, which are both exhibited in Figure 1. In contrast with the other two waters, a black tightly-adherent film developed on the wetted strip. Moreover, specimens with completely wetted strips in some instances exhibited breaks on the gauge length which did not intersect the wetted strip. It was assumed, initially, that such specimens should be discarded, but as further data were obtained it became clear that Helen water was insufficiently aggressive to promote corrosion fatigue to any important extent, and that breaks were likely to occur at any point in the gauge length, as in a plain fatigue test. Therefore, results obtained on specimens which showed fractures which did not intersect the wetted strips were also tabulated, provided the strip was completely wetted (Figure 7).

## 2. Corrosion Tests on ASTM 6061-T6 Aluminum Alloy

Subsequent to tests in the three mine waters, specimen surfaces were similar to those shown in Figure 2; that is, localized corrosion attack was clearly visible to the naked eye on specimens of the aluminum alloy tested in the Leitch and Levack mine waters. During tests in Helen water, on the other hand, a dark adherent film, similar to that observed in the corrosion fatigue tests, was produced. The film was usually quite uniform, as shown in Figure 2, though its appearance was in some cases patchy, possibly due to inadequate cleaning of specimen surfaces. In no case, however, was macroscopic localized corrosion attack observed, similar to that characteristic of the other two mine waters.

The results of the corrosion tests, including observed weight changes, are summarized in Table 6. It is seen that, in two of the mine waters, corrosion rates were too low to be measured in a test of only 24 hours duration. In the Levack water, which was more corrosive, the measured rate (in terms of a uniform attack) was also low, amounting to approximately 0.005 in./year.

## 3. Examination of Fatigued Specimens

Subsequent to the fatigue and corrosion fatigue tests, specimen surfaces were washed gently, to remove loose deposits, and examined using a stereomicroscope with a maximum magnification of 40X. In accordance with general experience(3,4) specimens broken in plain fatigue tests usually showed only a single failure crack. In contrast, specimens which had failed in corrosion fatigue tests usually showed systems of multiple cracks roughly parallel to the main failure. A number of cracks of this type are visible in specimen A-23-12 of Figure 1.

Examination of the surfaces of the four steels showed that relatively short exposures to Leitch mine water, which has an extremely high chloride content, had produced severe pitting in all cases. A cross section of two typically hemispherical pits is shown in Figure 8. For the T-1 and Stelcoloy G steels, but not for mild steel and Abrasive Resistant steel, the corrosion attack in this water appeared to become more uniform in specimens exposed for longer periods.

In contrast with the Leitch mine water, the Helen and Levack mine waters produced a more uniform and somewhat similar corrosion attack on the four steels. Although small and shallow pits were observed, the severity of pitting attack produced by the Leitch water at its worst was never equalled.

As noted previously, exposure of the 6061-T6 aluminum alloy to Helen mine water produced a dark, smooth, tightly-adherent deposit on the wetted strip, with no apparent loss of metal through corrosion. The other two waters produced a localized attack, the attack being apparently more severe in the Levack than in the Leitch mine water. Metallographic sections showed that the Levack mine water, unlike the Leitch mine water, was attacking the aluminum intergranularly (Figure 9).

## DISCUSSION OF RESULTS

### 1. Steels

There appeared to be slight but possibly significant differences in the corrosion fatigue strengths at $10^7$ cycles of the four steels, which showed values ranging from a low of 16,500 psi to a high of 23,000 psi (Table 4). Mild steel showed the highest average corrosion fatigue strength of nearly 22,000 psi, and Stelcoloy G steel showed the lowest average value, in the neighbourhood of 18,000 psi. The other two steels showed intermediate and similar average corrosion fatigue strengths. In view of the scatter shown in the data on Figures 3-7, further measurements would be required to establish the validity of the indicated trends. In agreement with general experience(3,4), there was no relationship between the average corrosion fatigue strengths and the tensile strengths of the steels.

The corrosion fatigue strengths of the four steels did not show any overall relationship to water type, and thus no general statement concerning the relative aggressiveness of the three water types on steel was warranted. It appeared, however, that each of the steels showed slight differences in behaviour in the three mine waters. These specific effects could not have been predicted, in most cases. However, it appeared significant that mild steel and Abrasive Resistant steel, which showed the greatest susceptibility to pitting corrosion in the high-chloride Leitch mine water, also showed their lowest corrosion fatigue strengths in this water.

Table 5 presents damage ratios for the metals, i.e. the ratios between corrosion fatigue and plain fatigue strengths at $10^7$ cycles. It is seen that mild steel exhibits the highest damage ratios and T-1 steel the lowest, of the four steels, with the other two steels showing intermediate values. Damage ratios are seen to decrease with increasing tensile strength and hardness of the steels, i.e. with their increasing susceptibility to fracture.

## 2. ASTM 6061-T6 Aluminum Alloy

The corrosion fatigue strengths at $10^7$ cycles for 6061-T6 aluminum alloy lay in the range 8,000-15,500 psi (Table 4). This range was much broader than observed for any of the steels, taken individually, and demonstrated the greater sensitivity of the aluminum alloy to water type. The damage ratios (Table 5) also showed considerable variability, ranging from a high of 1.0 to a low of 0.52.

The thin, black, tightly-adherent film produced by Helen water was undoubtedly highly protective, as the corrosion fatigue behaviour in this water showed little departure from the plain fatigue behaviour (Figure 7). X-ray diffraction measurements, carried out on portions of the film isolated from the aluminum alloy substrate, failed to show the existence of any crystalline compound. It is therefore assumed that the film is amorphous.

Apparently the pitting corrosion which occurred in the Leitch water was more damaging than the intergranular attack which occurred in the Levack water, though the latter appeared more severe, from a superficial examination.

The appearance of the specimens after the corrosion tests (Figure 2) indicated that waters in which localized corrosion attack occurs (such as Leitch and Levack) bring about pronounced reductions in corrosion fatigue resistance. In Helen water, on the other hand, in which corrosion attack appeared to be much more uniform, resistance to corrosion fatigue was excellent. It appears, therefore, that a qualitative estimate of the corrosion fatigue behaviour of an aluminum alloy might be obtained by a simple immersion corrosion test in a water of interest, followed by an examination to determine the uniformity of the corrosion attack.

In the short-term tests, the corrosion rates of 6061-T6 aluminum alloy in Helen and Leitch water were too low to be measured. However, the determination of corrosion rates by means of polarization methods, reported elsewhere(5), indicated clearly that Helen mine water was by far the least corrosive of the three waters.

## CONCLUSIONS AND FUTURE PROGRAM

In considering the significance of these results to the choice of metals for mine shaft conveyances, the much lower density of aluminum, as compared with iron, should be kept in mind. This factor obviously favours aluminum, because the weight of the conveyance itself enters into the calculation of the weight of ore which can be transported per load. It might therefore be more appropriate to compare the five metals in terms of ratios of fatigue strength to density and of corrosion fatigue strength to density, comparable to the tensile-strength-to-density ratios used in rating aerospace materials. The results of this research, in terms of these ratios, are listed in Table 7, and it is seen that the resistance of ASTM 6061-T6 aluminum alloy to corrosion fatigue appears to be equal or better than that of the steels in all mine waters.

It should be noted that, if the load-supporting metals in a mine shaft conveyance could be protected from corrosion by impervious coatings kept in excellent condition by careful maintenance, performance would be more appropriately assessed by means of fatigue strength/density ratios. These show the T-1 steel to be best and the mild steel worst, with the other three metals occupying an intermediate position (see Table 7).

Since conditions will vary widely from one mine to another, and many specific factors not discussed in this report could be important, considerable care will have to be exercised in drawing general conclusions from the data of this report. It is also evident that the failure of mine shaft conveyances through corrosion fatigue of the load-supporting members is only one of several possible failure modes, and that many other additional factors must be taken into account when deciding upon the safest and most economical method for extracting ore from a mine.

With the provision of the foregoing basic information on the corrosion fatigue behaviour of several structural metals in representative mine waters, the primary objectives of this work have been achieved.

## ACKNOWLEDGEMENTS

This work was made possible by the co-operation of numerous individuals from several organizations, whose assistance is gratefully acknowledged. Some of those participating are mentioned below.

Mr. M. A. Twidale, of the Fuels and Mining Practice Division, Mines Branch, obtained samples of mine shaft waters from a number of mines in Ontario with the co-operation of a number of mine employees and personnel of the Ontario Department of Mines. Messrs. W. H. Brokenshire and D. A. Scott of the International Nickel Company of Canada provided assistance and advice in obtaining the metals used in the program. Mr. J. F. J. Thomas of the Industrial Waters Section, Mineral Processing Division, Mines Branch, provided analyses of the waters and also supplied assistance in choosing the mine waters eventually decided upon for detailed study.

Mr. P. J. Todkill, of the Mechanical Testing Section, Physical Metallurgy Division, Mines Branch, provided both facilities for the fatigue testing and advice regarding experimental techniques, and the Mechanical Testing Section also tested the mechanical properties of the metals investigated. The Mineral Sciences Division, Mines Branch, supplied chemical and spectroscopic analyses.

Technicians providing assistance in carrying out the measurements included Mr. C. C. Smith, of the International Nickel Company of Canada; the late Mr. G. R. Brabazon, of the Mechanical Testing Section, Physical Metallurgy Division; and Messrs. B. G. Olivier and J. G. Garrison, both of the Corrosion Section, Physical Metallurgy Division. The macrophotographs

of corroded specimens were made by the photographic services of the Physical Metallurgy Division, and the drawings were made by the Drafting Services of the Physical Metallurgy division.

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5. G. J. Biefer, "Polarization Measurements on ASTM Type 6061-T6 Aluminum Alloy in Three Ontario Mine Shaft Waters", Mines Branch Technical Bulletin TB-73, Department of Mines and Technical Surveys, Ottawa, Canada, August 1965.

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GJB:(PES):KW

## TABLE 1

### Analyses of Structural Metals Used

| Element | Metal | | | | |
|---|---|---|---|---|---|
| | "T-1" Steel | "Abrasive Resistant" Steel | Mild Steel | "Stelcoloy G" Steel | ASTM 6061-T6 Aluminum |
| Al | 0.05 | 0.03 | < 0.01 | 0.03 | Base |
| As | - | - | - | - | - |
| C | 0.16 + | 0.33 + | 0.25 + | 0.23 + | - |
| Co | < 0.01 | 0.04 | 0.03 | - | - |
| Cr | 0.55 | < 0.01 | < 0.01 | 1.05 | 0.22 |
| Cu | 0.28 + | 0.10 + | 0.15 + | 0.40 | 0.15 |
| Fe | Base | Base | Base | Base | 0.40 |
| Mg | - | - | - | - | 0.90 |
| Mn | 0.67 | 1.10 | 0.40 | 0.40 | 0.30 |
| Mo | 0.60 | 0.03 | < 0.01 | - | - |
| Ni | 0.73 | 0.03 | 0.06 | 0.60 | - |
| P | 0.016 + | 0.016 + | 0.007 + | 0.015 + | - |
| S | 0.029 + | 0.024 + | 0.028 + | 0.031 + | - |
| Si | 0.23 | 0.29 | 0.02 | 0.3 | 0.4 |
| Sn | 0.017 | < 0.001 | < 0.001 | - | - |
| Ti | 0.01 | < 0.004 | < 0.004 | - | - |
| V | 0.04 | < 0.007 | < 0.007 | - | - |
| Zr | 0.08 | < 0.01 | < 0.01 | < 0.001 | - |

+ Chemical analysis. Remainder: semi-quantitative spectroscopic analysis

TABLE 2

Mechanical Properties of Structural Metals Used

| Metal | Mechanical Properties | | | |
|---|---|---|---|---|
| | UTS, psi | Y.S., 0.2% Offset, psi | Elong., % | Rockwell C Hardness |
| "T-1" Steel | 165,500 | 151,600 | 10.3 | 37 |
| "Abrasive Resistant" Steel | 103,100 | 69,100 | 25.0 | 17 |
| Mild Steel | 70,900 | 46,900 | 31.0 | -3 |
| "Stelcoloy G" Steel | 82,900 | 46,800 | 27.8 | 6 |
| ASTM 6061-T6 Aluminum | 45,800 | 42,300 | 18.5 | - |

## TABLE 3
## Analyses of Three Ontario Mine Waters (Levack, Helen, Leitch)*

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

MINES BRANCH
MINERAL PROCESSING DIVISION

INDUSTRIAL WATERS SECTION
40 Lydia Street, Ottawa, Ont.

ANALYSIS OF WATER SAMPLE(S)
*(In parts per million)*

| Location | | | |
|---|---|---|---|
| Source of water | Levack Mine | Helen Mine | Leitch Mine |
| Sampling point | | | |
| Reference | | | |
| Laboratory number | | | |
| Date of sampling | | | |
| Storage period (days) | | | |
| Temp. at sampling (°C) | | | |
| Temp. at testing (°C) | 22.8 | 23.7 | 24.1 |
| Appearance, odour, etc. | | | |
| Organic matter: Oxygen consumed ($KMnO_4$) | | 4 | |
| Chem. oxygen demand (C.O.D.) | | | |
| Ultra violet absorption ( mu) | | | |
| Carbon dioxide ($CO_2$), calculated | | 10 | 4 |
| pH | 3.4 | 7.2 | 7.6 |
| Colour (Hazen units) | 15 | 0 | 5 |
| Turbidity (Units) | 1.5 | 0 | 10 |
| Alkalinity as (-Phenolphthalein | 0 | 0.0 | 0.0 |
| $CaCO_3$ (-Total | 0 | 83.1 | 77.7 |
| Susp. matter, dried at 105°C | | | |
| " " ignited at 550°C | | | |
| Res. on evap., dried at 105°C | | 1,644 | |
| Loss on ignition at 550°C | | 353 | |
| Sp. conductance, micromhos at 25°C | 3,040 | 1,897 | 31,000 |
| Hardness as (Total | 1,175 | 1,079 | 2,054 |
| $CaCO_3$ (Non-carbonate | 0.0 | 996 | 1,977 |
| Calcium (Ca) | 405 | 245 | 744 |
| Magnesium (Mg) | 42 | 113 | 48 |
| Iron (Fe) Total | 0.46 | 0.06 | 1.4 |
| Dissolved | 0.36 | 0.0 | 0.11 |
| Aluminum (Al) | 1.4 | 0.3 | 0.12 |
| Manganese (Mn) Total | 3.5 | 0.29 | 2.0 |
| Dissolved | 3.0 | 0.00 | 1.2 |
| Copper (Cu) | 1.58 | 0.005 | 0.05 |
| Zinc (Zn) | 0.54 | 1.7 | 0.05 |
| Sodium (Na) | 119 | 25.0 | 6,870 |
| Potassium (K) | 16.6 | 8.4 | 33 |
| Ammonia ($NH_3$) | | | |
| | 23.8 | | |
| | 0.56 | | |
| Carbonate ($CO_3$) | 0.0 | 0.0 | 0.0 |
| Bicarbonate ($HCO_3$) | 0.0 | 101 | 94.7 |
| Sulphate ($SO_4$) | 685 | 830 | 126 |
| Chloride (Cl) | 629 | 125 | 12,078 |
| Fluoride (F) | 0.4 | 0.18 | 0.37 |
| Phosphate ($PO_4$) Total | 0.01 | 0.0 | 0.37 |
| Dissolved | | | |
| Nitrate ($NO_3$) | 0.3 | 37 | 19 |
| Silica ($SiO_2$) | 20 | 3.1 | 5.6 |
| Sum of constituents | 1,950 | 1,440 | 19,921 |
| % Sodium | 16 | 4.8 | 88 |
| Saturation index at test temperature | | 0.0 | 0.0 |
| Stability index at test temperature | | 7.2 | 7.6 |
| Sodium Absorption Ratio (SAR) | | 0.33 | |

* in parts per million unless otherwise stated.

**NOTE:** Details of the above terms and procedures are given in the booklet, procurable from the Industrial Waters Section, Mines Branch, 40 Lydia St., Ottawa 4, Ontario, entitled "Industrial Water Resources of Canada, Water Survey Report No. 1, Scope, Procedure and Interpretation of Survey Studies", by J.F.J. Thomas, Report No. 833, Department of Mines and Technical Surveys, Ottawa, Canada (1953).

## TABLE 4

## Fatigue and Corrosion Fatigue Strengths at $10^7$ cycles

| Metal | Fatigue Strength, psi | Corrosion Fatigue Strength, psi | | |
|---|---|---|---|---|
| | | In Levack Water | In Helen Water | In Leitch Water |
| "T-1" Steel | 60,000 | 19,000 | 21,000 | 22,000 |
| "Abrasive Resistant" Steel | 44,500 | 22,000 | 21,000 | 18,000 |
| Mild Steel | 31,000 | 22,000 | 23,000 | 20,000 |
| "Stelcoloy-G" Steel | 39,000 | 20,000 | 16,500 | 18,000 |
| ASTM 6061-T6 Aluminum | 15,500 | 10,000 | 15,500 | 8,000 |

## TABLE 5

## Comparison between Corrosion Fatigue and Fatigue Strengths

| Metal | Damage Ratios (Corrosion Fatigue to Fatigue Strength at $10^7$ cycles) | | |
|---|---|---|---|
| | In Levack Water | In Helen Water | In Leitch Water |
| "T-1" Steel | 0.32 | 0.35 | 0.37 |
| "Abrasive Resistant" Steel | 0.49 | 0.47 | 0.40 |
| Mild Steel | 0.71 | 0.74 | 0.65 |
| "Stelcoloy-G" Steel | 0.51 | 0.42 | 0.46 |
| ASTM 6061-T6 Aluminum | 0.65 | 1.00 | 0.52 |

## TABLE 6

## Results of Corrosion Tests on ASTM Type 6061-T6 Aluminum Alloy in the Mine Waters

| Mine Water | Corrosion Rate, mdd* | Macroscopic Surface Appearance |
|---|---|---|
| Helen | 0, 0, 0 | Uniform Corrosion, dark film |
| Leitch | 0, 0, 0 | Localized Corrosion |
| Levack | 12, 10, 11.5 | Localized Corrosion |

*Milligrams/decimetre$^2$/day.
100 mdd = 0.053 inch/year for aluminum alloys.

## TABLE 7

### Results in Terms of Strength-Weight Ratios

| Metal | Ratio, Fatigue Strength at $10^7$ cycles to Density, 1000 in. | Ratio, Corrosion Fatigue Strength at $10^7$ Cycles to Density, 1000 in. | | |
|---|---|---|---|---|
| | | In Levack Water | In Helen Water | In Leitch Water |
| "T-1" Steel | 215 | 68 | 75 | 79 |
| "Abrasive Resistant" Steel | 159 | 79 | 75 | 64.5 |
| Mild Steel | 107 | 79 | 82.5 | 71.5 |
| "Stelcoloy-G" Steel | 140 | 71.5 | 59 | 64.5 |
| ASTM 6061-T6 Aluminum | 159 | 103 | 159 | 82 |

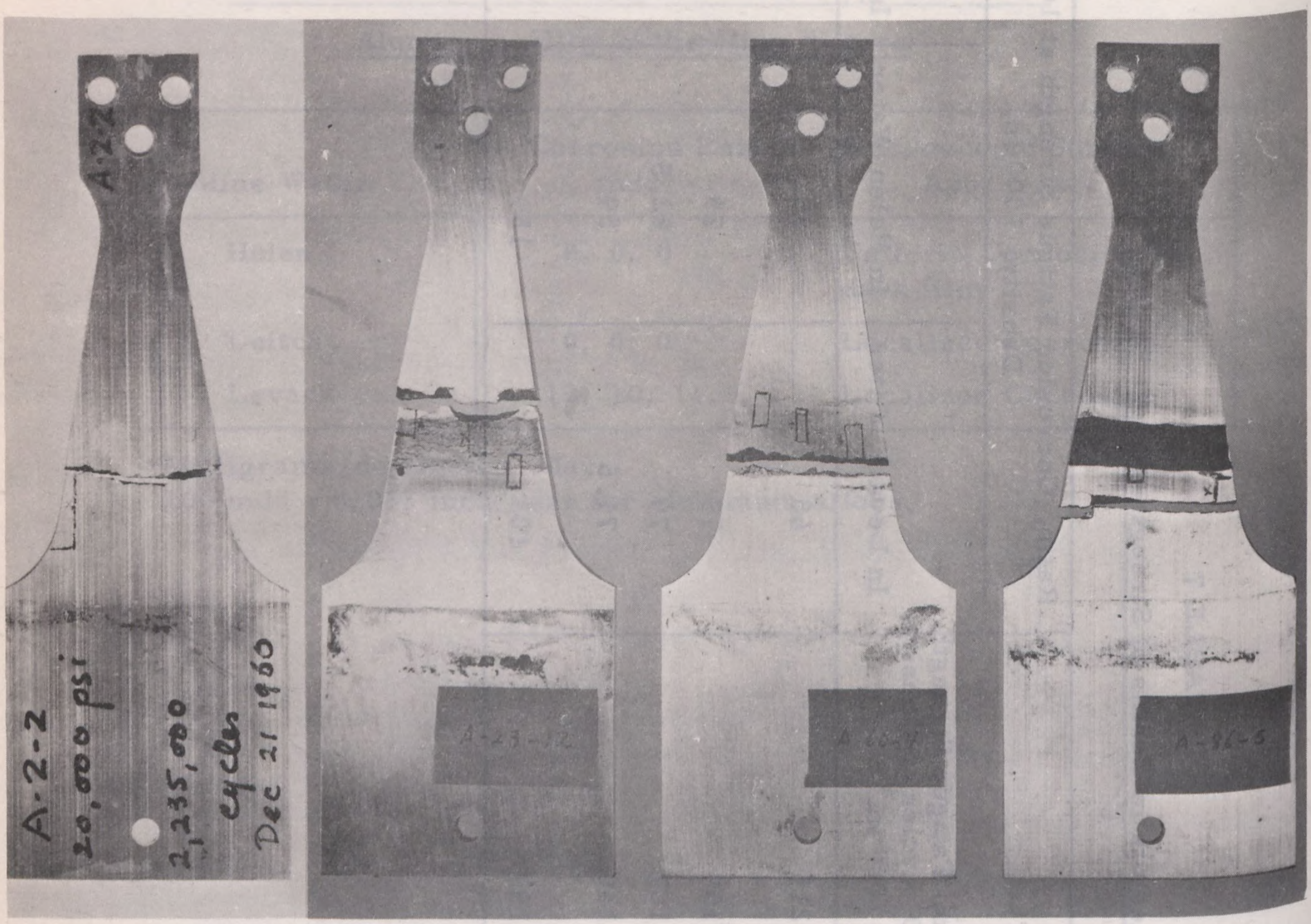

Figure 1. ASTM 6061-T6 aluminum alloy fatigue and corrosion fatigue specimens after testing.

The small rectangles on or near the wetted strips were added after testing to identify the areas where metallographic sections were taken. The specimen at the extreme left failed in plain fatigue. The three remaining specimens failed in corrosion fatigue tests in Levack, Leitch, and Helen mine waters (reading from left to right).

Magnification, X$\frac{1}{2}$.

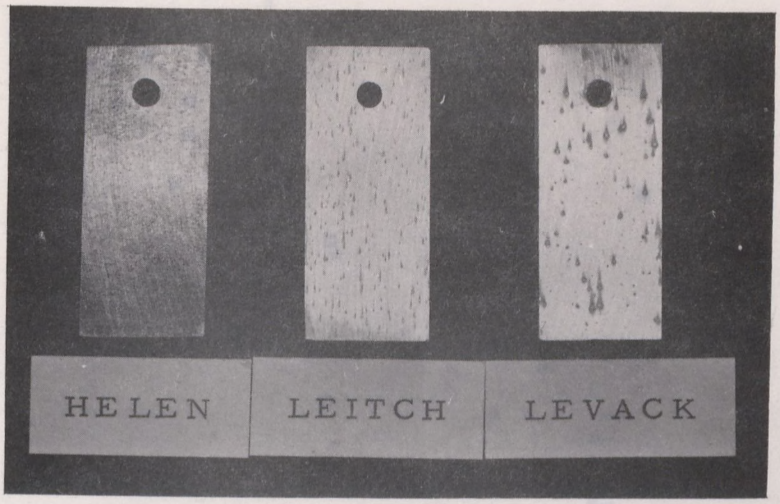

**Figure 2.** ASTM 6061-T6 aluminum alloy specimens subsequent to 24-hour corrosion tests in the three mine waters (Helen, Leitch, and Levack).

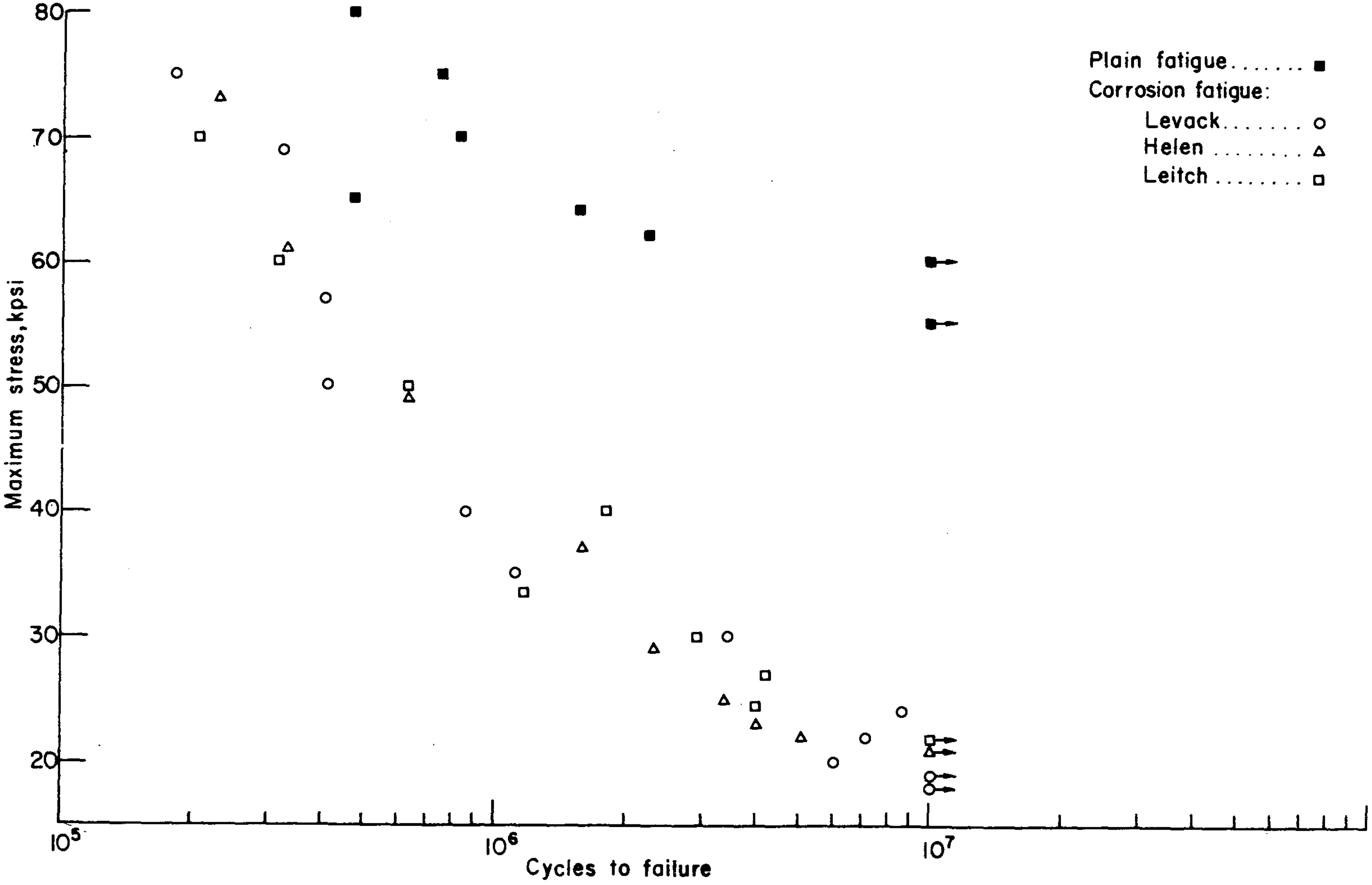

Figure 3. Fatigue and corrosion fatigue measurements on T-1 Steel (United States Steel Corporation).

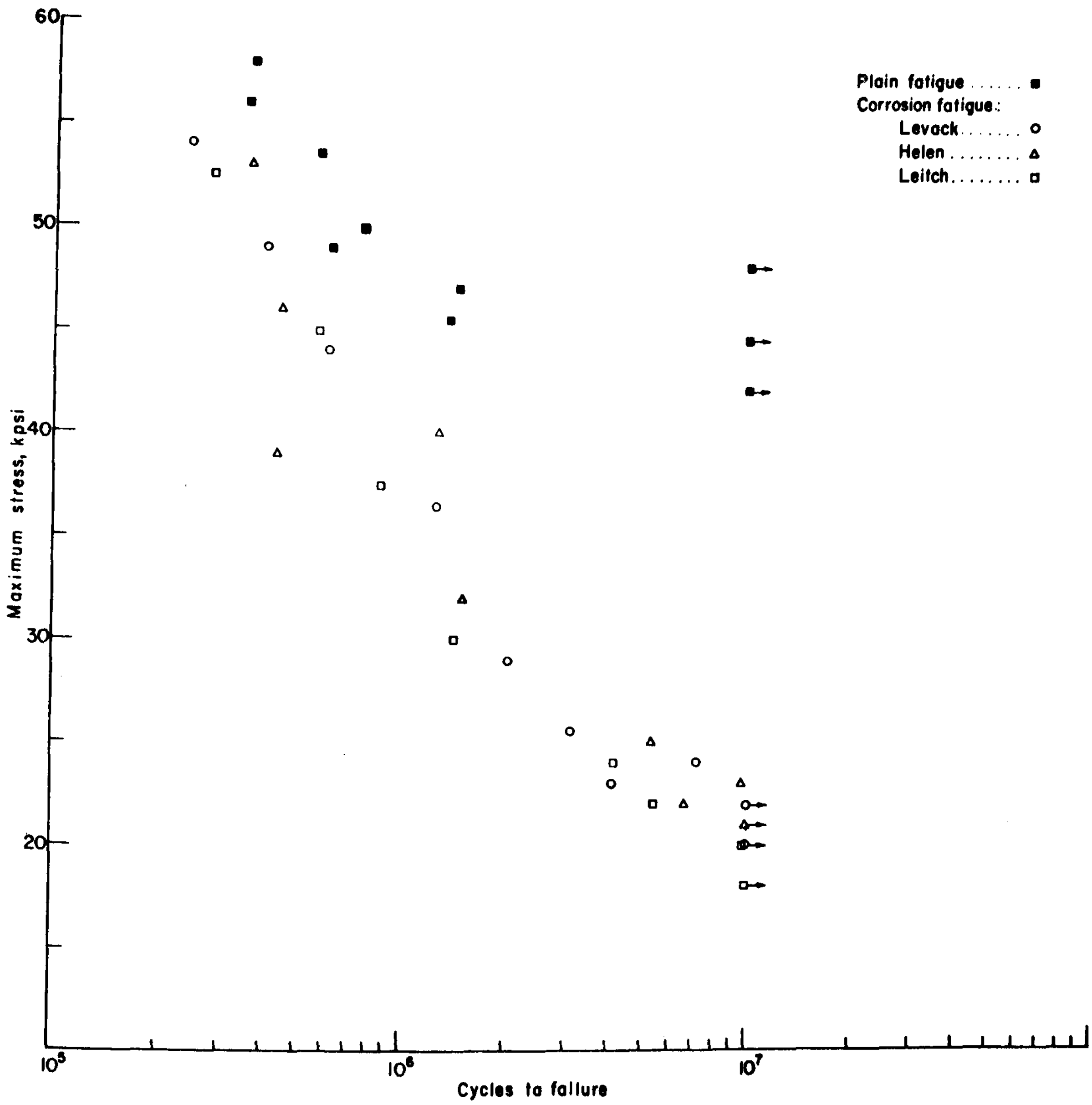

Figure 4. Fatigue and corrosion fatigue measurements on Abrasive-Resistant steel (The Steel Company of Canada Limited).

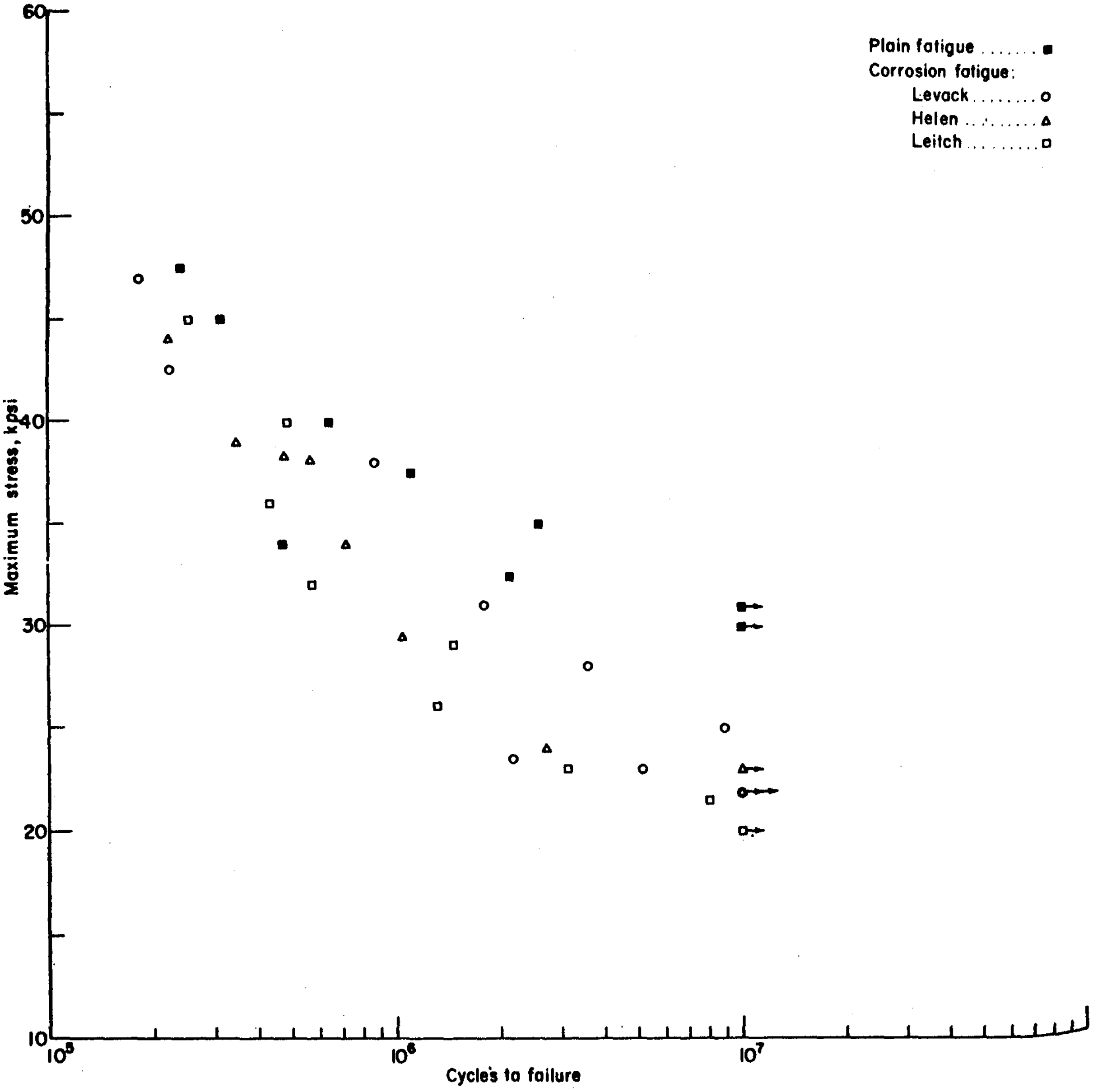

Figure 5. Fatigue and corrosion fatigue measurements on mild steel (ASTM Grade A-7).

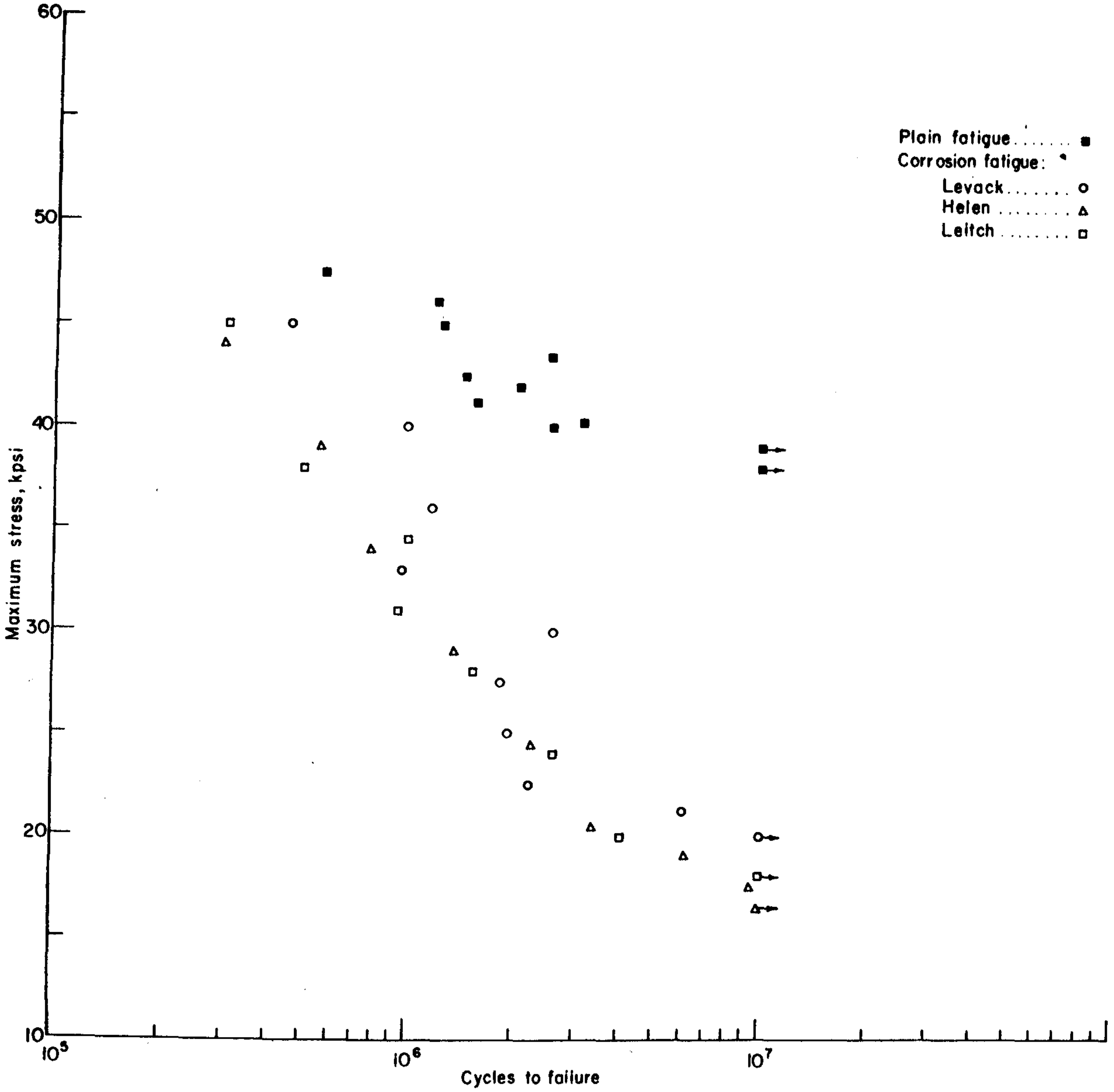

Figure 6. Fatigue and corrosion fatigue measurements on Stelcoloy G (The Steel Company of Canada Limited).

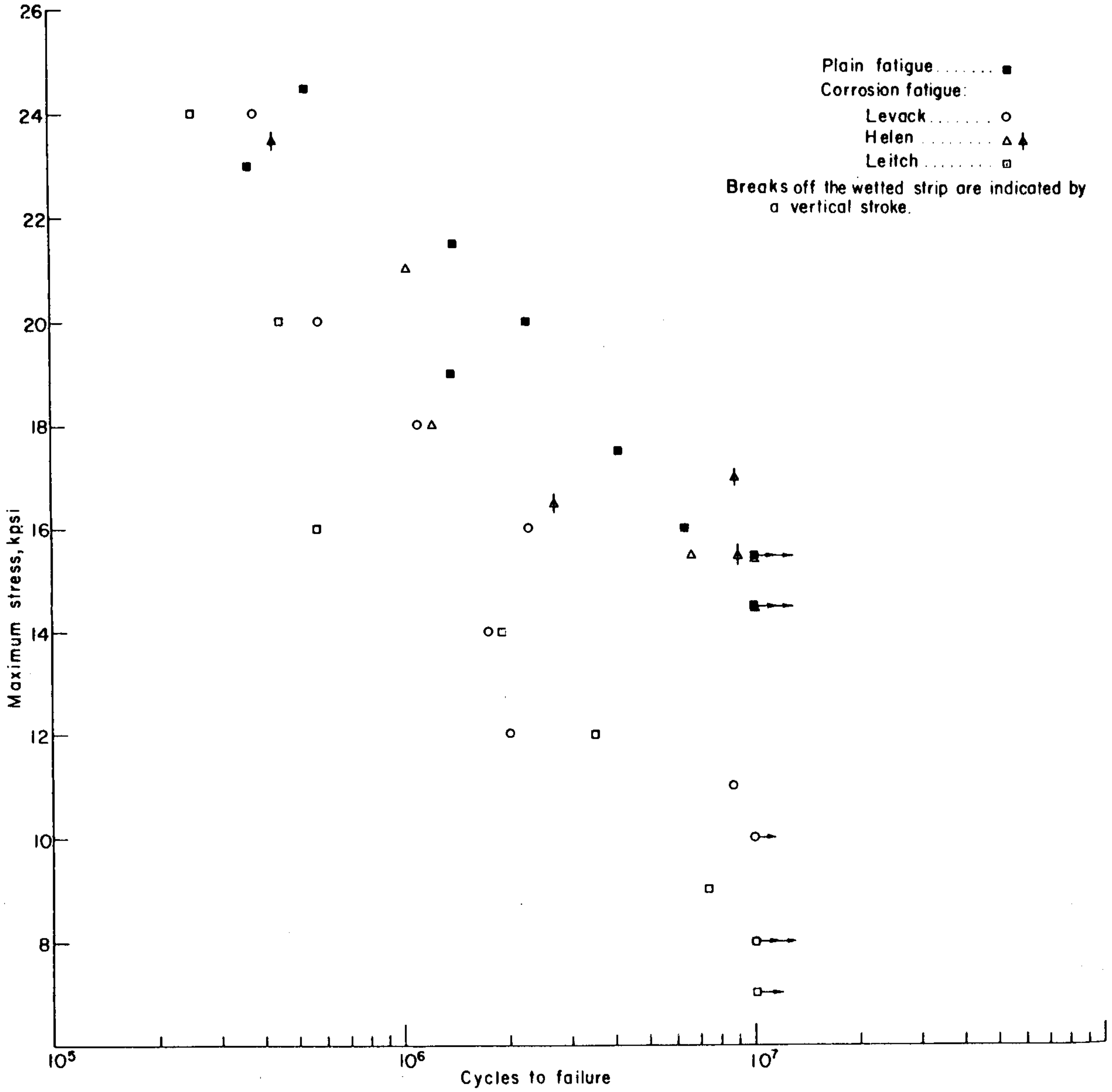

Figure 7. Fatigue and corrosion fatigue measurements on ASTM 6061-T6 aluminum alloy (Alcan 65S-T6, Aluminum Company of Canada Limited).

Figure 8. Corrosion pits in a mild steel specimen after exposure to Leitch mine water for about 24 hours in a corrosion fatigue test. Etched in 2% nital. X300.

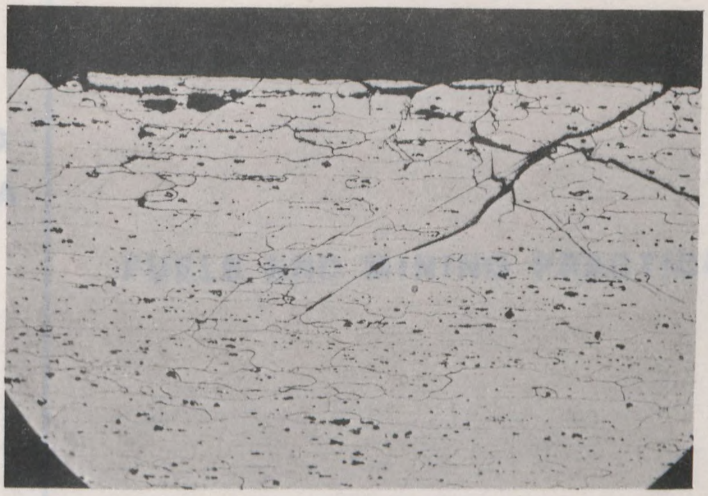

Figure 9. Cross section of corrosion fatigue cracks in a specimen of 6061-T6 aluminum alloy, subsequent to testing in Levack mine water, showing intergranular corrosion attack. Etched in modified Keller's reagent. X100.

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