Fifth Indian Expedition to Antarctica, Scientific Report, 1988
Department of Ocean Development, Technical Publication No. 5, pp. 431-441

Fracture and Fatigue Studies on Mild and Structural Steels For Use in Antarctica

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Abstract

This study was intended to determine the usability of ordinary mild and structural steels in the Antarctic climatic conditions. An attempt was made to improve the fatigue and fracture toughness characteristics of such metals for the above use. The effect of hydrogen removal on the Kpop-in value and the resulting fatigue crack growth rate and fatigue life of the metal specimen has been studied. An improvement in pop-in characteristics has been indicated.

Introduction

Many special alloys have been prescribed for and used in such low temperatures as are prevalent in the Antarctic. However, the high cost of these alloys inhibits their extensive use. Actual conditions in the place of use may permit the use of ordinary mild steels and structural steels. This makes it important to judge their suitability for such environs. This study assesses the fracture toughness and fatigue crack growth rate of mild and structural steels exposed to the Antarctic climatic cycle. Hydrogen in steel causes flaking and embrittlement. The effect of hydrogen removal is studied.

Materials and Method

Mild steel and structural steel samples were collected from the area in and around Dakshin Gangotri base station (70° 05'S; 12°E) and Schirmacher hill range (70°46'S; 11° 49'E to 12°E) from metal which has experienced the Antarctic climatic cycle for one year, two years and three years. Samples exposed for four years also were obtained from Schirmacher hill range. The samples were removed from position a few inches above the snow surface and a few inches below.

Some of the samples were removed from metal submerged in lakes which are shallow enough to freeze completely in winter.

The composition of the mild steel specimens:
C 0.10% to 0.17%; Mn 0.2% to 1.0%

The composition of the structural steel specimens:

C 0.15% to 0.28%; Mn 1.0% to 1.6%; P 0.04% to 0.45%
S 0.04% to 0.05%; Si 0.0% to 0.3%; Cu 0.0% to 0.2%

Specimen Preparation: The three-point bend specimens were prepared as per the specifications of ASTM E 399 (1). The span used was 200 mm, width 50 mm. Notch length 'a' is 20 mm, corresponding to a/W of 0.4.

The preparation of the specimen as per ASTM E399 is described in Fig 1.

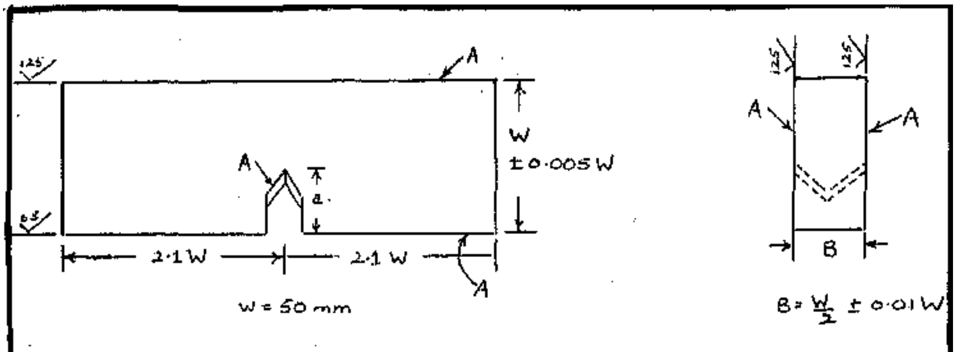

Fig. 1. Specimen preparation specifications

Hydrogen Analysis: The method consists of melting the sample of steel under low pressure in a graphite crucible at 1550 — 1700°C. Oxides, react with the carbon crucible and give carbon monoxide. The evolved gas is collected and analysed. 95% by volume is usually CO, the rest being nitrogen and hydrogen.

Vacuum *Annealing for Hydrogen Removal:* The specimens were heat treated in a 1 µm vacuum at 400°C for a period of 4 hrs. At the end of this period they were cooled to room temperature in vacuum. The furnace, of dimensions 8" X 11" X 24"(ht) required about 24 hrs to cool to room temperature. The temperature and duration used were considered suitable to obtain the required hydrogen removal from the material.

Fracture Toughness and FCGR Testing: The fracture toughness and fatigue crack growth rate (FCGR) testing was done on an MTS 810 system.

The three-point bend specimen aligned in the fixture and the clip gauge, which measures displacement, was inserted between the knife edges fitted on either side of the notch. Before the experiment began a table of EVB/P vs a/W was prepared.

The relationship used was—

$$EVB/P = f(a/W) = -45.8 + 711(a/W) - 3919(a/W)^2 + 11120(a/W)^3 - 15234(a/W)^4 + 8572(a/W)^5$$

for 0.3 a/W 0.7

Where

E = Young's modulus of elasticity, kN/mm^2

B = thickness of the specimen, mm

V = displacement measured by the clip gauge, mm

P = load applied, kN

a = crack length, mm

W = width of specimen, mm

Knowing EVB/P, a/W was determined from the table. The value of a/W thus obtained was used to calculate the K-calibration function F(a/W).

$$F(a/W) = \frac{6\sqrt{(a/W)}\,(1.99 - a/W(1 - a/W)\,(2.15 - 3.93(a/W) + 2.7(a/W)^2))}{(1 + 2(a/W))(1 - a/W)^{3/2}}$$

and the stress intensity factor, $\mathbf{K} = \frac{P}{B\sqrt{W}} \times F(a/W)$

The stress intensity value was always maintained below 15 MPa m to ensure that brittle fracture did not occur while testing. From the initial crack length known, the initial F(a/W) was obtained. The maximum load to be applied (P_{max}) was adjusted to obtain the required value of K.

In cyclic loading, P_{max}/P_{min} was maintained at 10, at a frequency of 19 Hz. As the crack grew, the value of F(a/W) increased. The load P_{mix} was hence decreased to ensure that K remained below the required limit. The exact value of F(a/W). was obtained by deriving a/W from E V B
p

In order to calculate E V B ,plots of P vs V were recorded periodically, The
P
slope of the plot (V/P) was used to calculate E V B. This precracking was continued
p
till a/W = 0.5.
For the FCGR analysis the number of loading cycles already experienced
(N)was noted each time the a/W was measured.
$\Delta a_= d a_= C (\Delta K)^m$
$\Delta N d N$

Where C and m are material constants to be determined experimentally.

$$\Delta K \text{ is } K_{max} - K_{min}$$

$$K_{max} = P_{max} \times \frac{F(a/W)}{B\sqrt{W}} \qquad K_{min} = P_{min} \times \frac{F(a/W)}{B\sqrt{W}}$$

The P_{max} and P_{min} values were reduced in steps and accordingly K_{mix} and K_{min} decreased. The cyclic loading was continued till crack extension occurred at each reduced step of load and K_{max} value reached 12 MPa m. This ensured that the crack tip was out of the plastic zone formed in the previous step of higher loads. In da/dN vs In ΔK was now plotted for FCGR analysis and values of C and m obtained.

Following these processes, monotonia loading was done for fracture toughness analysis. Record of the load (P) versus displacement (V) was made. The 5% secant method as described in ASTM E399 was used to obtain KQ, the conditional value of fracture toughness. If this value conforms to the conditions stipulated in ASTM E399, it is called the plane strain fracture toughness, KIC Pop-in occurring during monotonous loading was noted, and $K_{pop\text{-}in}$ calculated.

Results and Discussion

A. Mild Steel: Average values for one year old, two year old, three year old and four year old samples from Dakshin Gangotri area (DG) and Schirmacher hills (SH) are presented in Tables I-III

The Hydrogen Levels: Table I gives the levels of hydrogen in the mild steel specimens before and after vacuum annealing done at 400°C for 4 hrs at 1 µm vacuum.

Table I. Hydrogen Levels — Mild Steel

Specimen type	Initial Hydrogen (ppm)	Final Hydrogen (ppm)
DG(1)	1.8	0.9
DG(2)	1.8	1.0
DG(3)	1.6	0.9
SH(1)	1.7	0.9
SH(2)	1.5	0.9
SH(3)	1.8	0.8
SH(4)	1.6	0.9

DG — Dakshin Gangotri, SH — Schir macher hills. Number in brackets — Years of exposure to Antarctic climate.

Fracture Toughness: Table II gives fracture toughness values (K_{IC}).

Table II. Fracture Toughness of Mild Steels before annealing

Specimen type	$F(a_0/W)$	P_Q(kN)	K_{IC} (MPa m)
DG(1)	13.544	7.4	30.485
DG(2)	13.553	7.32	30.176
DG(3)	13.548	7.3	30.082
SH(1)	14.222	7.5	32.443
SH(2)	13.544	7.6	31.309
SH(3)	14.091	7.44	31.888
SH(4)	14.095	7.51	32.197

K_{IC} values after vacuum annealing are given in Table III.

Table III. Fracture Toughness of Mild Steels after hydrogen removal

Specimen type	$F(a_0/W)$	P_Q(kN)	K_{IC} (MPa m)
DG(1)	13.131	7.79	31.109
DG(2)	13.566	7.58	31.278
DG(3)	13.522	7.58	31.1.76
SH(1)	14.199	7.62	32.910
SH(2)	13.632	7.69	31.886
SH(3)	13.763	7,80	32.653
SH(4)	13.697	7.78	32.413

B. Structural Steel: Average values for one year old, two year old, three year old and four year old samples are presented.

Hydrogen Levels: Vacuum annealing was done for 4 hrs at 400°C at 1 *μm* vacuum. Table IV gives hydrogen levels before and after annealing.

Table IV. Hydrogen Levels — Structural Steels

Specimen type	Initial Hydrogen (ppm)	Final Hydrogen (ppm)
DG(1)	1:8	0.7
DG(2)	2.1	0.8
DG(3)	1.8	1.0
SH(1)	1.9	0.9
SH(2)	1.6	0.9
SH(3)	1.6	0.8
SH(4)	1.6	0.9

Fracture Toughness: Table V and VI give the K_{IC} and $K_{pop—in}$ values of structural steels.

Table V. Fracture Toughness of Structural Steels before annealing

Specimen type	$F(a_o/W)$	P_Q(kN)	K_{IC} (MPa Vm)	K_{pop-in}(MPa m)
DG(1)	13.828	6.885	28.95	22.69
DG(2)	13.107	6.950	27.70	24.10
DG{3)	13.151	6.900	27.60	21.09
SH(1)	12.998	7.139	28.22	23.06
SH(2)	13.981	7.000	29.76	22.91
SH(3)	13.544	7.009	28.87	22.95
SH(4)	13.784	6.995	29.32	21.20

Table VI. Fracture Toughness of Structural Steels after annealing

Specimen type	$F(a_0/W)$	P_Q(kN)	K_{IC} (MPa m)	K_{pop-in}(MPa m)
DG(1)	13.981	7.010	29.81	23.98
DG(2)	13.981	6.950	29.55	24.15
DG(3)	14.003	6.866	29.24	24.99
SH(1)	1.3.588	7.024	29.03	23.50
SH(2)	13.850	7.215	30.39	26.50
SH(3)	13.981	7.002	29.77	24.00
SH(4)	13.763	7.201	29.38	24.26

Fatigue Crack Growth Rate

Plots of In da/dN vs In ΔK for mild steel and structural steel yielded the following values of C and m :

$$\text{In } da/dN = \text{In } C + m(\ln \Delta K)$$

Mild steel: SH(1)* $m = 4.07$ $C = 6.92 \times 10^{-15}$
* 2,3 and 4 yr old specimens yielded similar results

DG(1) $m = 4.20$ $C = 7.05 \times 10^{-15}$
DG(3) m = 4;27 $C = 7.10 \times 10^{-15}$

Structural steel:

SH(1)* $M = 5.19$ $C = 5.33 \times 10^{-15}$
* 2,3 and 4 yr old specimens yielded similar results

DG(1) $m = 5.51$ $C = 5.80 \times 10^{-15}$
DG(3) $m = 5.71$ $C = 5.86 \times 10^{-15}$

Conclusions

1. The fracture toughness values obtained, indicated a decrease of 6.6% in the fracture toughness of *mild steel* samples from the *DG* area. The difference in fracture toughness between samples one year old and three year old was found to be 1.3%.

   The *Schirmacher hills* samples showed a drop in fracture toughness of 1.3%, as compared to an average standard value for similar compositions. No conclusion can be derived regarding the effect of the number of years of exposure.

2. The fracture toughness values after the *mild steel* specimens were vacuum annealed to *reduce hydrogen* levels by 47% on the average, indicated an improvement in K_{IC} values of 2%, for DG samples. *Schirmacher hills* specimens showed an improvement of 1.3% in K_{IC}

3. The fracture toughness of *structural steels* indicated a drop of 6.7% from average standard values for such steels. This was observed in the *DG* samples. 3 yr old specimens showed a 4% drop from values of 1 yr old samples. *Schirmacher hills* samples indicated a drop of 2.9% in fracture toughness compared to standard expected values. No conclusion can be drawn about the effect of the number of years of exposure.

4. After vacuum annealing the *structural steel* samples to *reduce hydrogen* the DG samples showed an improvement of 3% in K_{Ic} values. The *Schirmacher hills* specimens showed an improvement of 2% in K_{Ic} values.

5- $K_{pop\text{-}in}$ for *structural steel* specimens indicated an improvement by 9% on the average, after vacuum annealing.

6. The FCGR analysis of *mild steels* showed very little increase for the *Schirmacher hills* specimens, from standard expected values. The standard specimens showed a 2.6% increase in FCGR. FCGR of 3 year old specimens was 0.7% faster than FCGR of 1 year old samples from DG. Similar analysis of *structural steel* samples indicated the *Schirmacher hills* specimens were relatively unaffected, whereas *DG* samples showed a 10% faster FCGR. 3 year old samples exhibited an FCGR 1% faster than 1 year old samples.

Discussions

1. Fatigue Crack Growth Rate (FCGR) has a direct ' relationship with the expected life of a specimen. The expected life decreases to 50% of the original if FCGR is doubled. In mild steel and structural steel specimens, the FCGR was found to be faster by 2.6% and 10% respectively, as compared to expected values. This increase could be due to carbide precipitation around grain boundaries. Corrosion on the surface and within the metal was observed. This can be an additional factor, especially in Dakshin Gangotri samples where it was more prominent.

2. Reduction of hydrogen levels in the steels results in improved $K_{pop\text{-}in}$. A 10% increase in K_{pop_in} can result in a 2% increase in life expectancy. This can be considered a small but useful improvement. Improvement in fracture toughness by the order of 2% also helps improve loading capacity.

3. It may be suggested that steels with higher manganese contents be used. Manganese is an austenite stabiliser which also helps lower the carbide precipitation. Mild steels AISI-SAE 1015, 1006 and 1022 may be suggested for use. Structural steels require higher chromium levels and manganese levels. A242 and A440 may be suggested.

4. It is possible to continue to use relatively unmodified structural and mild steels in the Schirmacher area without adverse effects.

   In the Dakshin Gangotri area, the same steels can be used with higher chromium and manganese levels. The usefulness and actual effect of hydrogen removal is indicated in this report, but much more detailed analysis *is* required to corroborate these findings.

Suggestions for Further Work

This study has been carried out using samples collected at a particular time of the year. It would be more useful to carry out fatigue and fracture tests throughout the year, using samples exposed for periods in steps of one month. This would give a clear picture of the material state at each point in the Antarctic climatic cycle.

Reference

ASTM-E399 (1981): Standard Test Methods for plane strain fracture toughness of materials, *Annual Book of ASTM Stds,* Part ,10.