JOURNAL OF MATERIALS SCIENCE 21 (1986) 1927–1931

Environmental stress intensity for maraging steel

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Stress intensity, K, values for 18 Ni 1800 MPa maraging steel stressed to 90% of its K_{IC} level and exposed to water, hydraulic oil (servo 317) and water inhibited with 0.5, 1.0, 1.5 and 2% dichromate (pH about 7.5) for various durations were determined using the modified wedge opening loading (WOL) technique. Experiments revealed that there is no appreciable deterioration in K in oil and water inhibited with 1.5% and 2% dichromate even after 25 days exposure. The threshold stress intensity is reached after 15 days in 0.5% dichromate inhibited water at 40 MPa m$^{1/2}$. Stress corrosion crack growth rate in water is about 40 times the rate in hydraulic oil. Crack path characteristics of the WOL-tested maraging steel specimens in different environments are briefly mentioned.

1. Introduction

The use of 18 Ni 1800 MPa maraging steel in aerospace application involving different environments demands a more quantitative knowledge of the effects of environments on the behaviour of this material. Particularly the resistance to stress corrosion cracking (SCC) is required in quantitative terms useful to the designer. In an earlier investigation involving proof pressure test and subsequent burst testing of a maraging steel rocket motor case (2 m long, 0.3 m diameter and 0.0015 m thick) [1], tap water was found to be a satisfactory medium for the testing. However, for maraging steel rocket motor cases of larger thickness (of the order of 0.010 m), the evaluation of the stress intensity, K, of the material (stressed to 90% K_{IC} level and exposed to different media) for a longer duration (about 20 days or more) is essential to ensure that the reduction in K for the duration in the medium is well within the acceptable specified K, so that the material will withstand the proof pressure test satisfactorily.

Because such structures that are subjected to loads in hostile environments may contain small flaws, the significant method for quantitatively analysing this material for the critical application is the fracture mechanics approach. By testing pre-cracked specimens and analysing the data according to fracture mechanics concepts, a critical K can be determined below which unstable fracture cannot initiate [2]. The standard type of test specimens used for SCC studies by fracture mechanics approach are (i) cantilever beam type specimens [3–5] (single edge notch, SEN; double edge notch), (ii) three-point bend type test specimens [4], (iii) wedge opening lead (WOL) type specimens [6–8], and (iv) double cantilever beam (DCB) specimens [9] (straight and contoured DCB).

This paper presents the details of a series of experiments carried out to evaluate stress intensity values of 18 Ni 1800 MPa maraging steel using the modified WOL specimens [6], after stressing and exposing to different environments such as hydraulic oil (servo 317), water and water inhibited with 0.5, 1, 1.5, 2% sodium dichromate (pH of 7.5, i.e. mildly alkaline). The aim of the work was to find out the suitability of a medium for proof pressure testing of maraging steel motor cases of advanced launch vehicles.

2. Experimental techniques

The maraging steel procured from Misra Dhatu Nigam Limited (Midhani), Hyderabad and subsequently processed (forging, rolling and heat treatment) in our laboratory was used for the studies. Chemical analysis and properties of the material are given in Table I. 0.0125 m thick specimens of the WOL configuration (Fig. 1) in the solution-treated and aged condition (753 K for 3 h) were used for the experiments based on modified WOL technique [6]. The test specimens were fatigue precracked, as per ASTM E-399 [10], using a load ratio of $R = 0.1$, at 25 Hz frequency for 25 000 cycles. For comparison of K to evaluate the effect of stress and environment, a few precracked specimens were opened out in air and plane strain fracture toughness, K_{IC} values were calculated. The 10T Instron machine was used to give the required stress level of 90 MPa m$^{1/2}$ which corresponded to 90% of the specified K_{IC} for the material.

The stressed specimens were exposed to different media. The hydraulic oil used was of type servo 317. The water used for the experiments contained 36 p.p.m. chloride and had a conductivity of 0.15×10^{-6} mhos cm^{-1}. Laboratory grade sodium dichromate with an assay of min. 98%, chloride 0.03% max.,

TABLE I 18 Ni 1800 MPa maraging steel properties

(a) *Chemical composition* (wt %):
carbon 0.014; nickel 17.8; cobalt 8.07; molybdenum 4.8; titanium 0.53; aluminium 0.12; balance iron.

(b) *Mechanical properties* (solution treated and aged condition):

ultimate tensile strength	: 1910 MPa
yield strength (0.2%)	: 1849 MPa
elongation	: 13%

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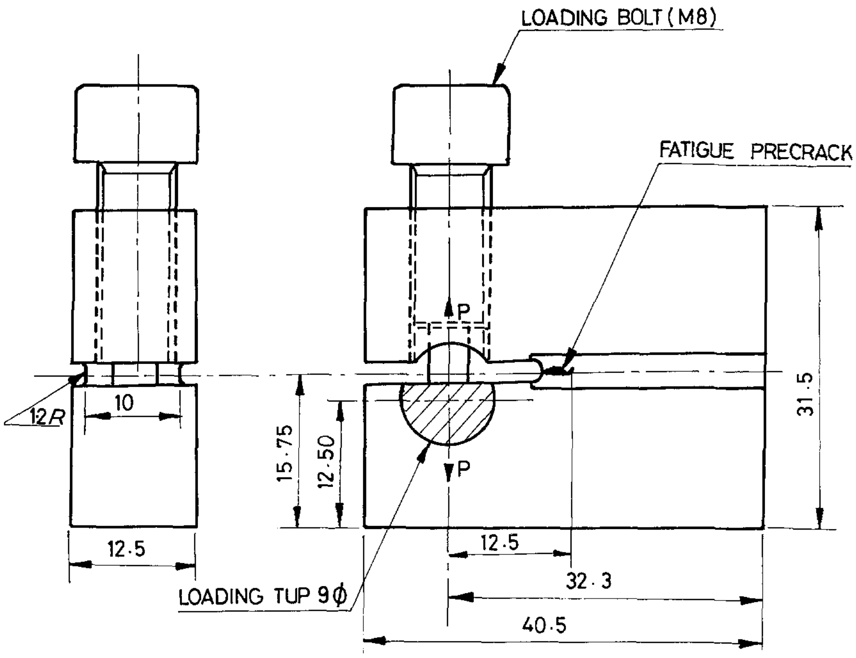

Figure 1 Modified WOL specimen with bolt and tup in position.

sulphate 0.2% and potassium 0.1% max., was used for the preparation of dichromate inhibited water of 0.5, 1, 1.5 and 2% concentrations. The details of preparation of this medium are described elsewhere [11]. After the required duration of exposure to different media (for 5, 10, 20 and 25 days and 41 days for some cases) the specimens were taken out, cleaned, rinsed and dried. Using the Instron 10T machine, the load level required for the particular crack displacement was evaluated for each specimen, which was then opened out to measure the crack length. The stress intensity values were calculated using the formula [6],

$$K_Q = \frac{P_Q C_3(a/w)}{Ba^{1/2}} \qquad (1)$$

where P_Q is the load, a the crack length, w the specimen width, B the specimen thickness, and $C_3(a/w)$ a function of (a/w) and is given by [6]

$$C_3(a/w) = 30.96(a/w) - 195.8(a/w)^2 + 730.6(a/w)^3 - 1186.3(a/w)^4 + 754.6(a/w)^5 \qquad (2)$$

The modified WOL configuration shown in Fig. 1 can be a self-stressed one without using a tensile machine [6]. The crack opening is fixed by the bolt and the loading is given by constant displacement (rather than by constant load as in a dead weight cantilever beam specimen). Because a constant crack opening displacement (COD) is maintained throughout the test, the force P, decreases as the crack length increases. Therefore, K_I decreases (a increases as P decreases) which leads to crack arrest. The effect of decrease in P more than compensates for the increase in a. Thus in this method only a single specimen is required to establish K_{ISCC} level because K_I approaches K_{ISCC} in the limit. However, duplicate specimens were tested to demonstrate reproducibility.

3. Results and discussion

The variation in stress intensity for 18 Ni 1800 MPa maraging steel stressed to about 90 MPa m$^{1/2}$ and exposed to oil (servo 317), water, water inhibited with 0.5, 1.0, 1.5 and 2% dichromate (pH about 7.5) for different durations are presented in Fig. 2. The data show that there is no decrease in K for oil, and no appreciable decrease in K in dichromate solutions of 1.5 and 2% up to 25 days. The results hold good even up to 41 days for oil and 2% dichromate solution. K in water deteriorates from 77 MPa m$^{1/2}$ for 5 days to 8 MPa m$^{1/2}$ for 20 days. It is also observed from Fig. 2 that the threshold stress intensity for SCC of the material is reached in 0.5% solution after 15 days at about 40 MPa m$^{1/2}$. Crack length measurements confirmed that for specimens exposed to 0.5% dichromate solution the crack arrest point has been reached after 15 days.

From Fig. 2 it is again clear that the lowering of K will be much less for durations less than 5 days in all the media. For longer durations, oil, 2% and 1.5% show no appreciable decrease in K, whereas 0.5% and water show drastic lowering in K values. 1% sodium dichromate solution is at the midway point between the two cases. Therefore, for test durations up to 25 days, it can be concluded from the data that dichromate solution of 2% and 1.5% with pH about 7.5 (i.e. mildly alkaline) could be used as the proof pressure medium. Hydraulic oil (servo 317) could be used for much longer duration.

Fig. 3 shows the variation in average stress corrosion crack growth rate (da/dt) for maraging steel in the different media. With respect to the initial crack length, a, the increase in crack length, da, on the opened out specimens after the required duration of exposure, t, was measured and da/dt evaluated. The da/dt is 5.0×10^{-10} m sec^{-1} in oil, 1×10^{-9} m sec^{-1} for 2% inhibited water, 2×10^{-9} m sec^{-1} for 1.5% dichromated water and increases to 20×10^{-9} m sec^{-1} for water. That is, the crack growth occurs 40 times faster in water than in oil.

Fig. 4 shows the fracture surfaces of the WOL specimens exposed to different environments and Fig. 5 gives the typical crack path characteristics in all the specimens. In an earlier investigation on K_{IC}-tested (in air) maraging steel specimens the authors had

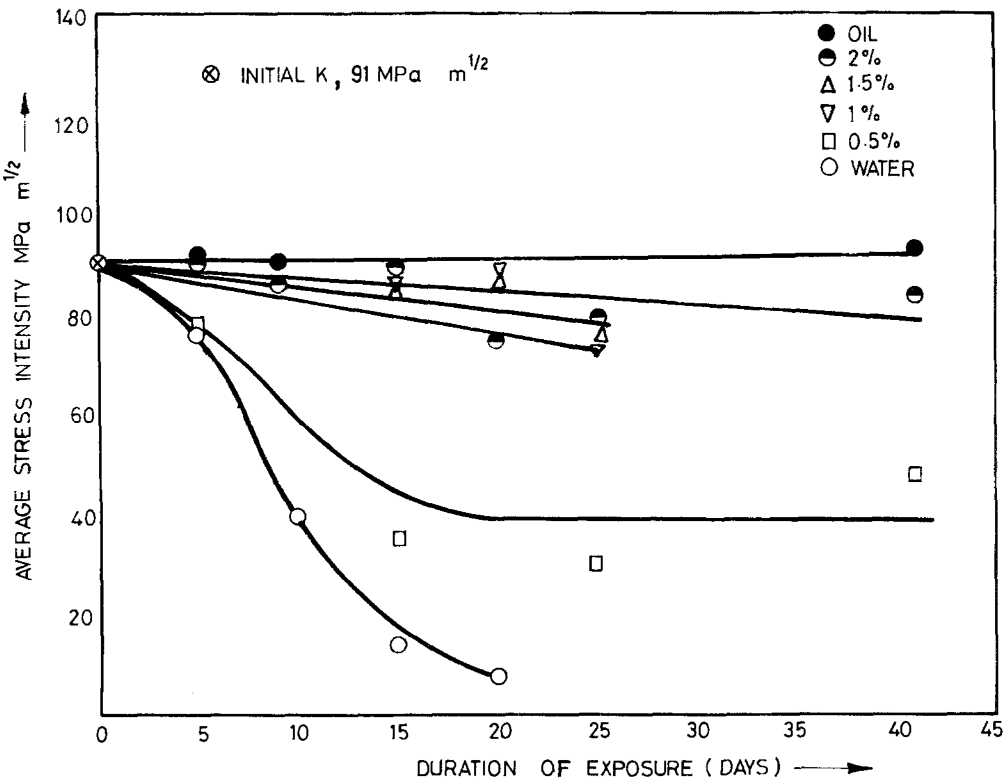

Figure 2 Variation of average stress intensity with exposure time in different environments.

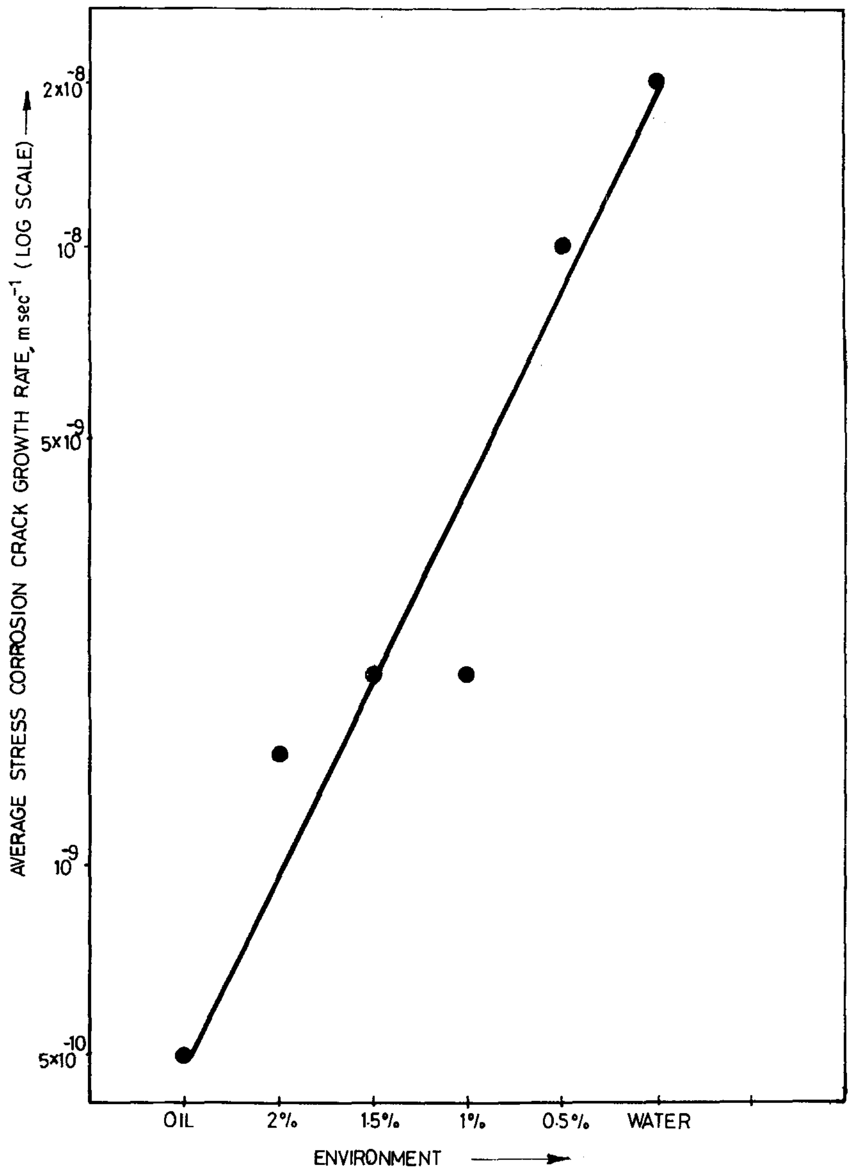

Figure 3 Average stress corrosion crack growth rate in different environments.

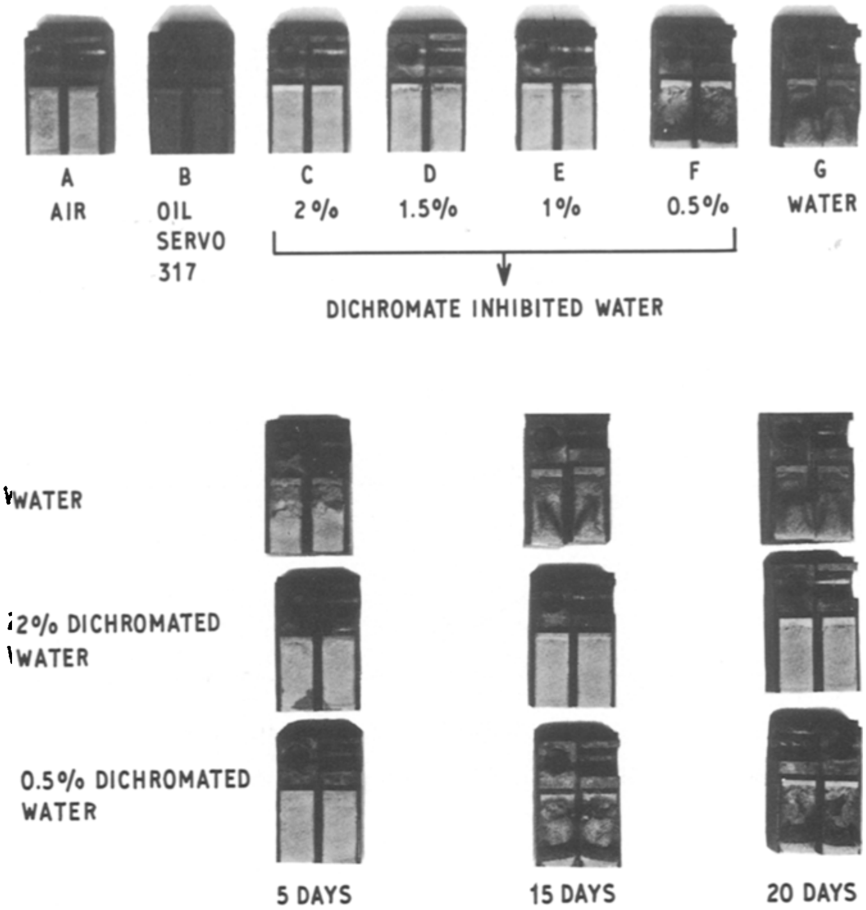

Figure 4 Fracture surface of typical WOL specimens exposed to different environments for various durations.

identified the crack path to be straight, and scanning electron microscopic (SEM) observations confirmed it to be intergranular [12]. The same straight path crack propagation (Fig. 5a) was observed here for WOL specimens tested in hydraulic oil and 2% dichromate solution. There was no deterioration in K in these environments even after long exposure (i.e. there was no SCC effect) and so the crack path was found to be intergranular. However, for water and 0.5% dichromate solution, both of which caused large deterioration in K and thus exhibited a pronounced SCC effect, crack branching was seen (Fig. 5b) even after short exposure indicating that the crack path was transgranular from the initial stages. For the other two media (1 and 1.5% dichromate solution) the deterioration in K was less and the crack path was straight for short exposure and subsequently crack branching (Fig. 5c) was observed for long exposure (10 days). This was a case of crack propagation mode changing from intergranular (short exposure) to transgranular (long exposure) when the SCC effect had become predominant. The SEM observations to reveal the crack morphology and its correlation with K will be presented elsewhere [13].

4. Conclusions

The following conclusions are drawn based on experiments on 18 Ni 1800 MPa maraging steel WOL

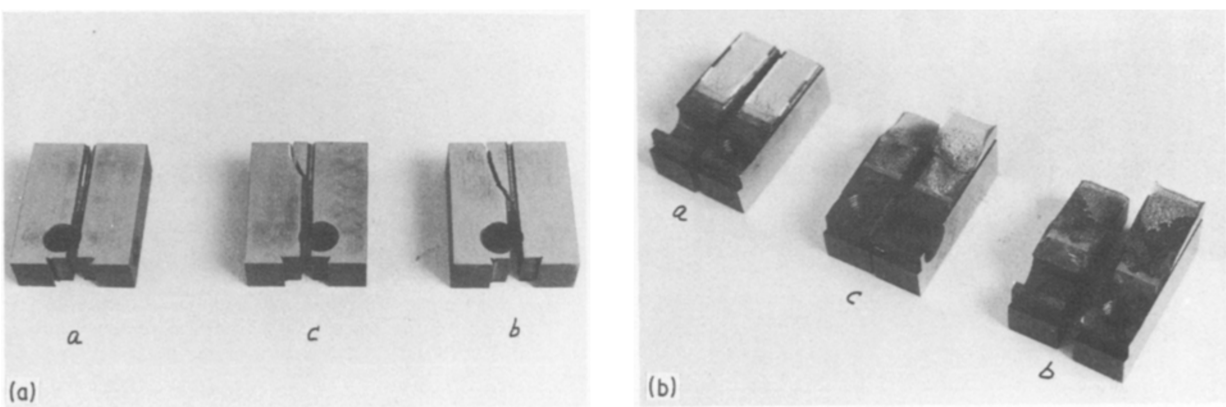

Figure 5 Crack paths in WOL-tested maraging steel specimens.

specimens, precracked, stressed to $90\,MPa\,m^{1/2}$ and exposed to different environments for various durations:

1. There is no deterioration in K in hydraulic oil up to 41 days. In water inhibited with 1.5 and 2% dichromate (pH about 7.5) up to 25 days the decrease in K is less than 10% and hence these three media are suitable for the proof pressure test.

2. For the 0.5% dichromate inhibited water, the threshold stress intensity for SCC, K_{ISCC}, is reached after 15 days at $40\,MPa\,m^{1/2}$.

3. The average stress corrosion crack growth rate varies from $5 \times 10^{-10}\,m\,sec^{-1}$ in oil to $20 \times 10^{-9}\,m\,sec^{-1}$ in water, a 40 fold increase in crack growth rate.

4. The crack path was straight in specimens tested in hydraulic oil and 2% dichromate solution. For specimens exposed to water and 0.5% dichromate solution crack branching (indicating transgranular mode) was observed even for shorter exposure times.

Acknowledgements
Assistance from colleagues in the Materials Group and Solid Motors Project is gratefully acknowledged. The authors thank Dr Vasant Gowariker, Director, VSSC, for his permission to publish this paper.

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Received 28 January
and accepted 12 July 1985