Crack growth characteristics of maraging steel

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Compact tension (CT) and surface crack tension (SCT) specimens of 18 Ni 1800 MPa grade maraging steel (parent metal and welded) were studied for the cyclic crack growth rate applying in sinusoidal (SL) and block loading (BL) conditions. The BL cycle was designed to simulate the stress intensity levels experienced during proof pressure and static test of a fabricated rocket motor. The threshold stress intensity for stage II crack growth for weldment is found to be about 0.6 that for the parent metal. For a given stress intensity, the crack growth rate for weldment and parent metal are in the same range under SL or BL. Through-thickness cracks (laboratory condition) in CT specimens and part-through thickness cracks (service condition) in SCT specimens show good correlation for cyclic crack growth rate. The results are of great significance for considering the reuse of the maraging steel rocket motor case.

1. Introduction

A good candidate material for the fabrication of the solid booster case of larger size launch vehicles is 18 Ni 1800 MPa (M250) grade maraging steel [1]. The high cost of the material and the fabrication intricacies have necessitated the possible reuse of the booster case on subsequent flights. Reuse can be effectively established if material data on sustained and cyclic stress crack growth rates are available for general and specific conditions. In an earlier investigation by the authors [2], sustained stress crack growth data were evaluated for 18 Ni 1800 MPa grade maraging steel. Hence a series of experiments were carried out on both parent and weldments of this material to establish the cyclic crack growth rate data. Two types of experiments were planned, namely sinusoidal loading (SL) condition to derive da/dN, where a is the crack length and N is number of cycles and block loading (BL) condition simulating a proof pressure and static test which will be carried out on the fabricated motor case and repeating the loading condition to arrive at the crack growth data after a fixed number of BL cycles. The Appendix shows the salient features of SL and BL conditions. The establishment of crack growth data for number of reuses will ensure the adequacy of the safety margin in the design of the motor case. The BL cycle was designed to simulate the stress intensity levels experienced during proof pressure and also during the static test of the fabricated motor case [3]. This paper brings out the results of crack growth experiments carried out on 18 Ni 1800 MPa maraging steel (parent and welded) specimens.

2. Experimental procedure

Plates of 0.0078 m thickness 18 Ni 1800 MPa maraging steel, both parent and weldment, were used for fabricating the following specimens of ASTM E399, E647, E740 standards [4]: $W = 2B$ CT specimen, parent and weldment; CT specimen, parent; and surface crack tension (SCT) specimen, parent and weldment. An Instron Model 8033 testing machine was used for all experiments.

2.1. Fatigue precracking

$W = 2B$ CT specimens were subjected to fatigue precracking to an initial a/w of 0.3. $W = 6B$ CT specimens were fatigue precracked to different initial a/w values of 0.3, 0.35, 0.4, 0.5, 0.55, 0.6 and 0.7 (W = width, B = thickness of specimen, a = crack length). The SCT specimens were precracked to a surface crack length of $2C = 0.003$ m in the solutionized condition and then maraged at 753 K for 3 h.

2.2. Crack growth by sinusoidal loading

The crack growth was observed through a travelling microscope. The crack growth da/cycle was evaluated. The load ΔP applied to each specimen was used in Equation 1 to evaluate ΔK [4–6]:

$$\Delta K = \frac{\Delta P}{BW^{1/2}} \frac{(2 + \alpha)}{(1 - \alpha)^{3/2}} \times (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \quad (1)$$

where B = thickness, W = width, α = a/w and a = crack length.

The $W = 2B$ autowelded and aged CT specimens were subjected to fatigue crack growth after initial precracking. Here the unloading compliance method [7] was used and the load against crack opening displacement (COD) plots for unloading were taken at every 10 000 cycle interval up to 100 000 cycles and at every 500 cycles thereafter. The crack growth da was calculated from the unloading compliance and the load P used for each specimen was taken to evaluate K using Equation 1.

In the case of SCT specimens [8], after making an initial precrack in the solutionized condition for 0.003 m length, specimens were maraged at 753 K for 3 h, then further subjected to sinusoidal loading to

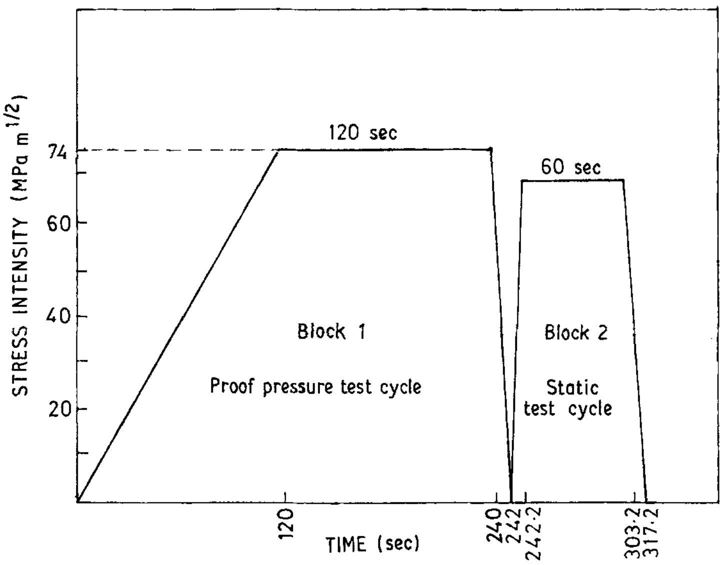

Figure 1 Schematic diagram of block loading (BL).

grow the crack to different lengths. The three point bend method was used with a stress level of 820 MPa (corresponding to $35\,\mathrm{MPa\,m^{-1}}$ stress intensity level) for these experiments. The number of cycles required for such crack growth was noted. The surface crack length 2C and crack depth a were measured on the broken halves of the heat-tinted tested specimen using a shadow graph. The parameters $\mathrm{d}2c/\mathrm{d}N$ and $\mathrm{d}a/\mathrm{d}N$ were evaluated. Both parent metal and weldments of SCT specimens were used in the test.

2.3. Crack growth by block loading

The autowelded and maraged $W = 2B$, CT specimens, after fatigue precracking, were subjected to the BL cycle as shown in Fig. 1. After each BL cycle, a plot of load against COD for loading and unloading was taken. The details on the number of cycles of BL and the loading levels are given in Table I. The unloading compliance method was used to calculate da. Similar BL cycles were applied to the SCT specimen.

3. Results and discussion

3.1. Sinusoidal loading

The data in Fig. 2 for parent metal are obtained from both $W = 6B$ and $W = 2B$, CT specimens, whereas the weld data are from $W = 2B$ specimens only. It is seen from Fig. 2 that the scatter in the data is minimal. The plots show the linear portion (stage II) of the Paris equation [9], $\log \mathrm{d}a/\mathrm{d}N = \log C + n \log \Delta K$. The constants C and n are evaluated from the data as 1.05×10^{-10} and 2.2 for parent metal and 0.27×10^{-10} and 2.7 for weldment, respectively. It is interesting to note that the threshold stress intensity for stage II crack growth for weldment is 0.6 that for parent metal. This is due to the embrittlement effect caused by the welding process. Also for a given stress intensity in SL condition (e.g. $K = 35\,\mathrm{MPa\,m^{-1}}$) the cyclic crack growth rate $\mathrm{d}a/\mathrm{d}N$ for weldment and parent metal are in the same range (0.2 to 0.3 μ/cycle). However, once initiated the crack growth rate increases linearly with ΔK for both parent metal and weldment till they reach the K_{Ic} level when failure occurs catastrophically. The experiments on parent metal and weldments of SCT specimens yielded a crack growth rate of 0.1 to 0.2 μ/cycle. Another interesting observation in the SCT specimen is that the growth per cycle in surface crack length 2C is about three times that in crack depth a.

TABLE I Block loading data for CT specimens

Autowelded; $W = 2B$; $B = 7.5$ mm; precracked to various a/w			$\mathrm{d}a/\mathrm{d}N$ μ/cycles	Remarks
Sl. No.	No. of BL cycles N	Load P KN		
1	50	7.35	9.6	a/w = 0.5, failed at P = 8.80 KN after 50 cycles
2	50	6.98	10.2	a/w = 0.5, failed at P = 7.8 KN after 50 cycles
3	50	7.74	18.2	a/w = 0.5, failed at P = 8.34 KN after 50 cycles
4	50	7.75	14	a/w = 0.5, failed at P = 8.14 KN after 50 cycles
5	2	3.72	1.1	a/w = 0.4, specimen did not
	20	4.90	2.0	fail even after 185 cycles,
	135	6.34	5.0	since initial low loading at
	185	8.33		P = 3.73 KN
6	1	5.88		a/w = 0.4, specimen did not
	105	6.34	1.8	fail even after 165 cycles,
	135	7.85	3.0	since initial low loading at
	150	8.33	6.0	P = 5.88 KN
	165	8.82	7.0	

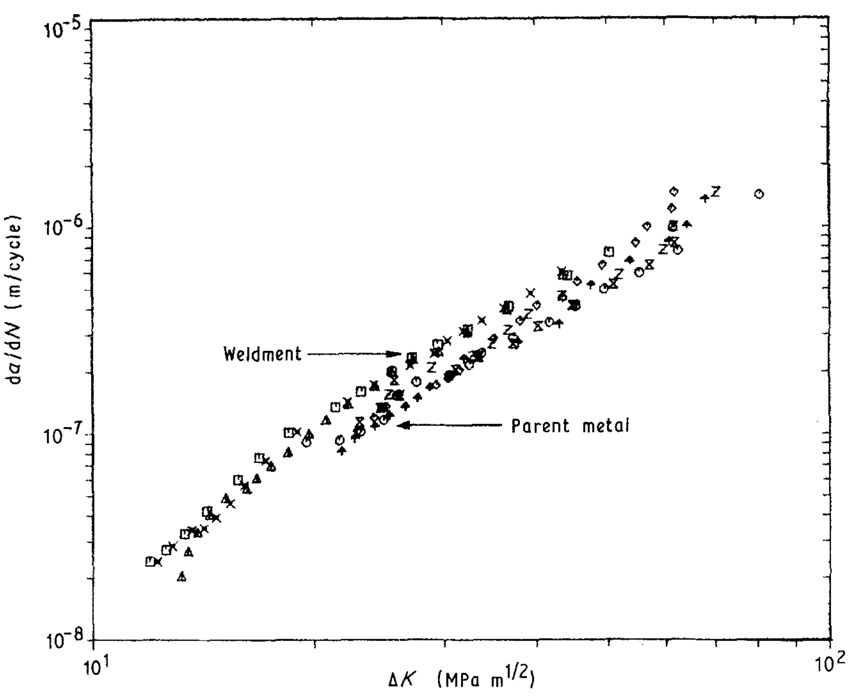

Figure 2 da/dN against ΔK plots for parent metal and weldments.

3.2. Block loading

The experiments were carried out on autowelded CT specimens with $W = 2B$. Interesting observations were made during BL experiments which simulated the service condition (Fig. 1) of the proof pressure test and static test of a fabricated motor. From Table I, it is seen that when the initial loading is high (7.35 KN corresponding to a stress intensity level of 74 MPa m^{-1}) there is a sudden initial high crack growth rate after the first BL cycle. This is due to the fact that plasticity setting in at the crack tip since K will fall very near to stage III of the crack growth curve of weldment. Formation of this plastic zone retards further crack growth which is seen as very small or negligible da/dN during subsequent BL cycles. When the load level is raised high enough, corresponding to K_{Ic} of the material, fast failure took place. On the other hand, if the initial loading is low (3.73KN corresponding to stress intensities of 38 MPa m^{-1}) the crack growth rate increases with the increasing number of BL cycles as expected from stage II behaviour for weldment. In this case, also after a few repeated BL cycles at lower loads, when subsequent loading is raised to higher level, an increase in da/dN with increasing BL is noticed. The average crack growth rate is about 3 μm/BL cycle. Similar experiments on welded SCT specimens yielded average da/dN of 4.5 μm/BL cycle.

It is to be noted that there is a difference in configuration of cracks between CT and SCT specimens. Through-thickness cracks are generated in CT specimens, whereas part-through cracks, which are closer to practical situations in a fabricated rocket motor case, are generated in SCT specimens. However, SL and BL experiments on both CT and SCT specimens have yielded values for crack growth rate da/dN in the same range. It is also observed that da/dN for BL is an order of magnitude higher than that for SL condition. This is an important observation for the correlation of data on da/dN between the laboratory and service conditions.

4. Conclusions

1. Crack growth studies conducted on 18 Ni 1800 MPa grade maraging steel CT specimens parent metal and weldment have yielded Paris law constants C and n as 1.05×10^{-10} and 2.2 and 0.27×10^{-10} and 2.7, respectively.

2. From SL experiments on CT specimens, the threshold stress intensity for stage II crack growth in the weldment is 0.6 that for parent metal. The crack growth rate in weldment and parent metal fall in the same range.

3. The SL experiments on SCT specimens yielded a crack growth rate for parent metal and weldment in the same range. The growth per SL cycle in surface crack length 2C is about three times that in crack depth, a.

4. The BL experiments in CT specimen revealed that a plastic zone forms at the crack tip and retards the crack growth for further repeated BL if the initial load is high enough to induce stress intensity levels of the order of 74 MPa m^{-1} corresponding to stage III, ΔK at the crack tip. If the initial loading at the crack tip is low, the crack grows as the BL is repeated. The average crack growth rate is 3 μm BL cycle.

5. In the case of the part-through crack (SCT welded specimen), the average crack growth rate is 4.5 μm/BL cycle.

6. For BL da/dN is an order of magnitude higher than that for SL for both crack configurations.

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Appendix: Salient features of SL and BL conditions for constant amplitude crack growth studies

1. The two wave forms are different. SL is sinusoidal whereas BL is a trapezoidal type wave (Fig. 1).

2. One SL cycle takes 0.05 sec (for frequency of 20 Hz) whereas on BL cycle (block 1 + block 2 of Fig. 1) takes 317 sec.

3. The frequency of loading for SL can be 20 Hz or 30 Hz, but for BL programme it is 0.003 Hz.

4. The load applied for SL is 1.48 *KN* wheras for BL it is 6.9 *KN*.

5. The net section stress, σn, is the stress on the net section or ligament [10] is:

$$\sigma N = \frac{2P(2W + a)}{B(W - a)^2}$$

where P = load, W = width and B = thickness of specimen and a = crack depth. For $W = 0.015$ m, $B = 0.0075$ m and $a = 0.0075$, σN for SL = 266 MPa and for BL, it is 1244 MPa, i.e. σN is 15% of yield stress for SL and 75% yield stress for BL. Also for BL, σN is applied in 0.2 sec at a dynamic rate of 34.5 *KN* sec and sustained for 2 min in block 2. This process may lead to the setting in of plasticity at the crack tip.

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