NRL Report 7936

# Effect of Specimen Thickness on Fatigue Crack-Growth Rate in 5Ni-Cr-Mo-V Steel Comparison of Heat-Treated and Stress-Relieved Specimens

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Ship structural design now incorporates the weight-saving advantage of high-strength alloys by reducing the thickness requirements of load-bearing members. For fail-safe applications of thin-section material (less than 0.50 in. (12.5 mm) thick) in high-performance ship structures, quantitative information concerning the fatigue crack-growth rate (FCGR) in both ambient air and the marine environment is highly important. The paucity and diverse conclusions of presently available information concerning the effect of material thickness on FCGR provides little engineering guidance for the design of thin-section naval structures.

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This study of FCGR on a 5Ni-Cr-Mo-V steel tested in three thicknesses indicates that internal residual stresses may have a retardation effect on FCGR in this material. When tested after stress relief, although crack growth is accelerated, it is essentially the same for all thicknesses.

## CONTENTS

## SYMBOLS

| | |
|---|---|
| $a$ | Total crack length of a CT specimen measured from the load point |
| $a_0$ | Initial crack length |
| $a/W$ | Crack length-to-width ratio |
| B | Specimen thickness |
| CCT | Center-crack tension specimen |
| COD | Crack-opening displacment |
| CT | Compact tension specimen |
| da/dN | Crack growth rate; change in length per cycle |
| E | Young's modulus |
| FCGR | Fatigue crack-growth rate |
| h | Specimen half height |
| $\Delta K$ | Stress-intensity-factor range |
| $\Delta K_{eff}$ | Stress-intensity-factor range corrected for the effect of stress ratio R |
| P | Load |
| PTC | Part-through-crack specimen |
| N | Number of cycles |
| R | Stress ratio; $\sigma_{min}/\sigma_{max}$ |
| $r_{xy}$ | Correlation coefficient |
| W | Specimen width |

# EFFECT OF SPECIMEN THICKNESS ON FATIGUE CRACK-GROWTH RATE IN 5Ni-Cr-Mo-V STEEL — COMPARISON OF HEAT-TREATED AND STRESS-RELIEVED SPECIMENS

## INTRODUCTION

The use of high-strength alloys in marine structural design saves weight since material of thinner gage may be used. Structural-integrity technology for such high-performance structures, however, requires information concerning crack-growth fracture resistance. Specifically, material for structures subjected to intermittent loading must be analyzed for fatigue crack-growth rate (FCGR) both in ambient and marine environments.

Although a prolific literature exists on the subject of FCGR, surprisingly little explores the effect of material thickness, which is recognized as a factor of major importance. The information that does exist provides limited engineering guidance since three types of response are documented: (a) no effect of thickness [1 – 4]; (b) growth accelerated by increased thickness [5, 6]; (c) growth accelerated by decreased thickness [7, 8]. Further, little of the available information is relevant to the design of naval structures.

The information presented here systematically explores the FCGR characteristics of 5Ni-Cr-Mo-V steel in three thicknesses, 0.25, 0.50, and 0.90 in. (6.25, 12.50, and 22.50 mm), in the as-heat-treated and stress-relieved conditions. Specimens were machined as centercuts from a well-characterized 1.0-in. (25.4-mm) thick rolled plate of this quenched-and-tempered alloy steel.

## EXPERIMENTAL CONSIDERATIONS

### Material

The 5Ni-Cr-Mo-V steel used for this series of tests has been extensively studied in the 0.90-in. (22.5-mm) thickness [9, 10]. Details of composition, heat treatment, and mechanical properties are to be found in Tables 1 and 2.

Table 1a
Composition of 5Ni-Cr-Mo-V Steel

| Element | C | Ni | Cr | Mo | V | Al | Mn | P | S | Si | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage | 0.11 | 4.85 | 0.58 | 0.48 | 0.07 | 0.01 | 180.87 | 0.002 | 0.005 | 0.30 | Balance |

Table 1b
Heat Treatment

| |
|---|
| Normalized: 1640°F; 1-1/2 hr; water quench |
| Austenitized: 1525°F; 1-1/2 hr; water quench |
| Tempered: 1050-1130°F; 1-1/2 hr; water quench |
| Stress relieved (SR): 1000°F; 30 min; air cool |

Note: Manuscript submitted September 26, 1975.

Table 2
Mechanical Properties of Heat-Treated
5Ni-Cr-Mo-V Steel

| Property | Direction | |
|---|---|---|
| | Longitudinal | Transverse |
| Yield strength (0.2% offset) (ksi) | 142 | 147 |
| Tensile strength (ksi) | 152 | 152 |
| Elongation (%) | 20 | 18 |
| Reduction of area (%) | 68 | 64 |

## Specimen Geometry

The dimensions of the compact tension (CT) specimen (Fig. 1) conform to those selected for the ASTM E24.04 round-robin program [11]. However, to provide a longer fatigue crack extension beyond the machined notch, the initial notch length $a_0$ was reduced from 0.70 to 0.50 in. (17.5 to 12.5 mm). All specimens were machined in the ASTM designated T-L orientation [12].

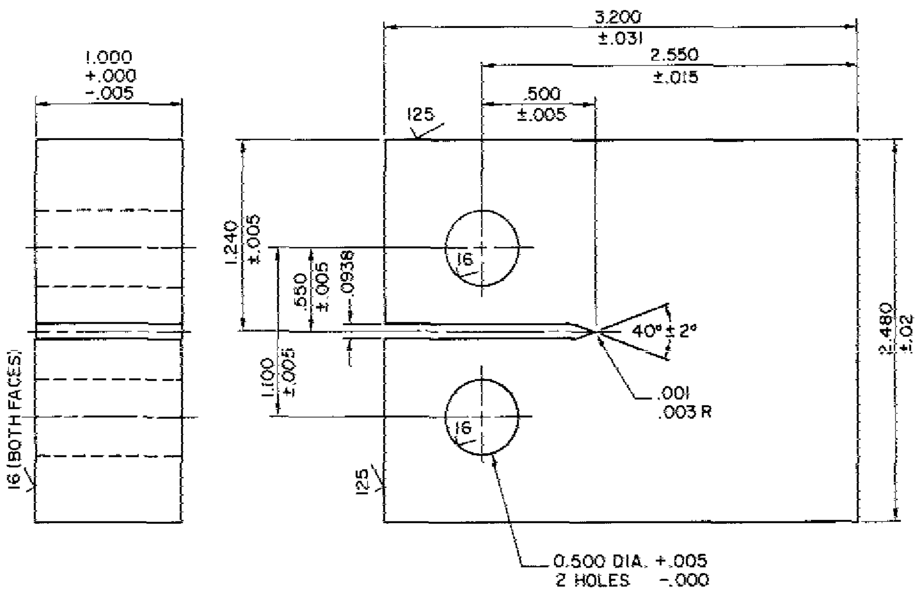



Fig. 1 — Compact tension specimen

### Test Procedure

Specimens were cycled in tension-tension loading using a haversine waveform on a 110-kip-capacity MTS closed-loop testing machine. The cyclic frequency was 5 Hz, and the stress ratio R was 0.10. Crack-length measurements were made using a crack-opening displacment (COD) technique [10, 13]. A commercial MTS COD clip gage was used, the notched arms of which fit over knife edges screwed on to the specimen to straddle the mouth of the machined notch. Signals from the COD strain gage circuit were fed into a Hewlett-Packard XY recorder together with those from the load cell of the testing machine.

Loads were chosen to give predetermined $\Delta K$ values so that there would be a slight overlap of the $\Delta K$ values in the two tests made at each specimen thickness (Table 3).

Table 3
Details of Crack Growth Tests; R = 0.1, Cyclic Frequency = 5 Hz.

| Specimen Number | Thickness B (in.) | $\Delta P$ (kip) | $\Delta a$ (ksi) | $\Delta K_{eff}$ (ksi $\sqrt{in.}$) | | $\Delta K_{eff}$ (ksi $\sqrt{in.}$) | |
|---|---|---|---|---|---|---|---|
| | | | | Start | Final | a = 0.825 | a = 1.400 |
| As Heat Treated | | | | | | | |
| 856 | 0.25 | 1.11 | 1.74 | 17.2 | 39.2 | 19.6 | 33.3 |
| 855 | 0.25 | 1.74 | 2.74 | 27.0 | 61.7 | 30.8 | 52.4 |
| 854 | 0.50 | 2.22 | 1.74 | 17.2 | 39.2 | 19.6 | 33.3 |
| 853 | 0.50 | 3.48 | 2.74 | 27.0 | 61.7 | 30.8 | 52.4 |
| 844 | 0.90 | 4.04 | 1.74 | 17.2 | 38.6 | 19.6 | 33.3 |
| 845 | 0.90 | 4.04 | 1.74 | 17.2 | 38.6 | 19.6 | 33.3 |
| 847 | 0.90 | 9.76 | 4.25 | 41.3 | 94.2 | 47.0 | 80.1 |
| As Stress Relieved | | | | | | | |
| 858 | 0.25 | 1.11 | 1.74 | 17.2 | 34.2 | 19.6 | 33.3 |
| 860 | 0.25 | 1.74 | 2.74 | 27.0 | 52.4 | 30.8 | 52.4 |
| 863 | 0.50 | 2.22 | 1.74 | 17.2 | 37.8 | 19.6 | 33.3 |
| 861 | 0.50 | 3.48 | 2.74 | 27.0 | 59.6 | 30.8 | 52.4 |
| 859 | 0.90 | 4.04 | 1.74 | 17.2 | 37.8 | 19.6 | 33.3 |
| 862 | 0.90 | 6.28 | 2.74 | 27.0 | 61.7 | 30.8 | 52.4 |

## Data Reduction

Crack length was determined by reference to the predetermined EB[COD]/P-vs-a/W caliabration curve, where E is Young's modulus; B is the specimen thickness; P is the load; a is the crack length; and W is the specimen width. A polynominal expression for this relationship is

$$\frac{a}{W} = 0.01520 \frac{EB[COD]}{P} - 0.000141 \left(\frac{EB[COD]}{P}\right)^2 + 0.000000524 \left(\frac{EB[COD]}{P}\right)^3 - 0.06209 . \quad (1)$$

Details of this procedural technique are available [10]. Crack-growth rate was determined by fitting tangents to the a-vs-N curves using a Bausch and Lomb split-prism tangent meter.

The stress-intensity-factor range $\Delta K$ is computed from the equation appropriate to the 0.486 height-to-width ratio h/W of the specimen [14]: $\Delta K = \Delta\sigma\sqrt{a}\,Y$, where

$$Y = 30.96 - 195.8 \frac{a}{W} + 730.6 \left(\frac{a}{W}\right)^2 - 1186.3 \left(\frac{a}{W}\right)^3 + 754.6 \left(\frac{a}{W}\right)^4 . \quad (2)$$

Tables 4 and 5 contain values of crack length a, $\Delta K$, and da/dN for all specimens tested in this investigation.

## DISCUSSION OF EXPERIMENTAL RESULTS

The experimental results of this investigation are shown in Figs. 2a and 2b, which are logarithmic plots of crack-growth rate da/dN vs stress-intensity-factor range $\Delta K$. Data from specimens tested in the as-heat-treated conditions are shown in Fig. 2a, and data from heat-treated plus stress-relieved specimens are shown in Fig. 2b. In both figures comparison is made to a trend line previously established for 0.90-in. (22.5-mm) thick (nearly full plate thickness) as-heat-treated specimens of this same material. The regression-curve equation for this trend line is

$$\frac{da}{dN} = 3.04 \times 10^{-9}\, \Delta K_{eff}^{2.26} . \quad (3)$$

This equation was established using the part-through-crack (PTC) specimen geometry [9, 10]. Figure 3 shows the trend-line equation together with data from three types of fracture mechanics specimens (CT, PTC, and CCT); good correlation is apparent.

Table 4a
5Ni-Cr-Mo-V Steel; Heat Treated; $\Delta\sigma$ = 1.74 ksi.

| Specimen Number: | | 856 | 854 | | 844 | 845 |
|---|---|---|---|---|---|---|
| Thickness B (in.): | | 0.25 | 0.50 | | 0.90 | 0.90 |
| Crack Length a (in.) | $\Delta K$ (ksi $\sqrt{in.}$) | da/dN $\times 10^{-6}$ | | $\Delta K$ (ksi $\sqrt{in.}$) | da/dN $\times 10^{-6}$ | |
| 0.825 | 19.6 | 2.33 | 3.37 | 19.3 | 2.29 | 2.60 |
| 0.850 | 20.0 | 2.54 | 4.00 | 10.6 | 2.41 | 2.68 |
| 0.875 | 20.4 | 2.77 | 4.34 | 20.1 | 2.54 | 2.82 |
| 0.900 | 20.8 | 3.00 | 4.66 | 20.5 | 2.68 | 3.08 |
| 0.925 | 21.2 | 3.12 | 4.82 | 21.0 | 2.82 | 3.20 |
| 0.950 | 21.7 | 3.31 | 5.00 | 21.4 | 2.88 | 3.44 |
| 0.975 | 22.2 | 3.50 | 5.27 | 21.8 | 3.08 | 3.64 |
| 1.000 | 22.7 | 3.70 | 5.55 | 22.4 | 3.26 | 3.74 |
| 1.025 | 23.2 | 3.91 | 5.75 | 22.8 | 3.38 | 3.92 |
| 1.050 | 23.7 | 4.34 | 5.96 | 23.4 | 3.73 | 4.16 |
| 1.075 | 24.2 | 4.66 | 6.17 | 23.8 | 3.92 | 4.51 |
| 1.100 | 24.8 | 5.00 | 6.40 | 24.4 | 4.16 | 4.74 |
| 1.125 | 25.3 | 5.42 | 6.64 | 25.0 | 4.90 | 4.91 |
| 1.150 | 25.9 | 5.75 | 7.04 | 25.5 | 5.24 | 5.12 |
| 1.175 | 56.5 | 6.17 | 7.28 | 26.1 | 5.36 | 5.62 |
| 1.200 | 27.1 | 6.40 | 7.55 | 26.7 | 5.75 | 6.04 |
| 1.225 | 27.7 | 7.01 | 7.84 | 27.3 | 6.18 | 6.34 |
| 1.250 | 28.4 | 7.70 | 8.42 | 28.0 | 6.51 | 6.51 |
| 1.275 | 29.1 | 8.00 | 9.40 | 28.7 | 6.86 | 6.86 |
| 1.300 | 29.8 | 8.32 | 10.40 | 29.4 | 7.26 | 7.47 |
| 1.325 | 30.6 | 9.81 | 11.44 | 30.2 | 7.69 | 7.93 |
| 1.350 | 31.4 | 10.97 | 12.38 | 31.0 | 7.92 | 8.72 |
| 1.378 | 32.4 | 11.78 | 13.02 | 31.4 | 8.18 | 9.33 |
| 1.400 | 33.3 | 12.38 | 14.46 | 32.8 | 8.72 | 10.02 |

Table 4b
5Ni-Cr-Mo-V Steel;
Heat Treated; $\Delta\sigma$ = 2.74.

| Specimen Number: | | 855 | 853 |
|---|---|---|---|
| Thickness B (in.): | | 0.25 | 0.50 |
| Crack Length a (in.) | $\Delta K$ (ksi $\sqrt{in.}$) | da/dN $\times 10^{-6}$ | |
| 0.825 | 30.8 | 9.4 | 11.11 |
| 0.850 | 31.4 | 10.1 | 11.30 |
| 0.875 | 32.1 | 10.4 | 11.50 |
| 0.900 | 32.8 | 10.8 | 11.70 |
| 0.925 | 33.4 | 11.4 | 11.92 |
| 0.950 | 34.2 | 12.2 | 12.13 |
| 0.975 | 35.0 | 12.5 | 12.40 |
| 1.000 | 35.8 | 12.9 | 12.80 |
| 1.025 | 36.5 | 13.4 | 13.02 |
| 1.050 | 37.3 | 13.8 | 13.27 |
| 1.075 | 38.2 | 14.4 | 13.90 |
| 1.100 | 39.0 | 14.9 | 14.30 |
| 1.125 | 39.8 | 16.0 | 14.80 |
| 1.150 | 40.8 | 16.6 | 15.20 |
| 1.175 | 41.8 | 17.5 | 16.00 |
| 1.200 | 42.7 | 18.2 | 16.64 |
| 1.225 | 43.7 | 18.5 | 17.60 |
| 1.250 | 44.8 | 19.2 | 18.40 |
| 1.278 | 45.8 | 20.0 | 19.40 |
| 1.300 | 47.0 | 20.8 | 20.50 |
| 1.325 | 48.2 | 22.6 | 22.40 |
| 1.350 | 49.5 | 24.5 | 24.80 |
| 1.375 | 50.9 | 25.6 | 26.10 |
| 1.400 | 52.4 | 28.7 | 27.40 |

Table 4c
5Ni-Cr-Mo-V Steel;
Heat Treated; $\Delta\sigma$ = 4.25 ksi.

| Specimen Number: | | 847 |
|---|---|---|
| Thickness B (in.): | | 0.90 |
| Crack Length a (in.) | $\Delta K$ (ksi $\sqrt{in.}$) | da/dN $\times 10^{-6}$ |
| 0.825 | 47.0 | 20.00 |
| 0.850 | 48.0 | 20.56 |
| 0.875 | 49.0 | 21.82 |
| 0.900 | 50.0 | 23.41 |
| 0.925 | 51.1 | 24.26 |
| 0.950 | 52.2 | 24.70 |
| 0.975 | 53.3 | 25.14 |
| 1.000 | 54.5 | 26.06 |
| 1.025 | 55.8 | 27.52 |
| 1.050 | 57.0 | 28.56 |
| 1.075 | 58.2 | 29.68 |
| 1.100 | 59.5 | 30.56 |
| 1.125 | 60.8 | 32.64 |
| 1.150 | 62.2 | 33.95 |
| 1.175 | 63.8 | 34.64 |
| 1.200 | 65.2 | 37.61 |
| 1.225 | 66.6 | 39.20 |
| 1.250 | 68.4 | 41.00 |
| 1.275 | 70.0 | 42.89 |
| 1.300 | 71.8 | 44.92 |
| 1.325 | 73.7 | 47.12 |
| 1.350 | 75.6 | 49.50 |
| 1.375 | 77.8 | 52.10 |
| 1.400 | 80.1 | 59.77 |

Table 5a
5Ni-Cr-Mo-V Steel;
Stress Relieved; $\Delta\sigma$ = 1.74 ksi.

| Specimen Number: | | 858 | 863 | 859 |
|---|---|---|---|---|
| Thickness B (in.): | | 0.25 | 0.50 | 0.90 |
| Crack Length a (in.) | $\Delta K$ (ksi $\sqrt{in.}$) | da/dN × $10^{-6}$ | | |
| 0.825 | 19.6 | 2.88 | 3.82 | 3.40 |
| 0.850 | 20.0 | 3.12 | 4.13 | 3.81 |
| 0.875 | 20.4 | 3.31 | 4.55 | 4.20 |
| 0.900 | 20.8 | 3.50 | 5.00 | 4.50 |
| 0.925 | 21.2 | 3.84 | 5.18 | 4.74 |
| 0.950 | 21.7 | 4.04 | 5.27 | 4.91 |
| 0.975 | 22.2 | 4.34 | 5.36 | 5.18 |
| 1.000 | 22.7 | 4.50 | 5.55 | 5.55 |
| 1.025 | 23.2 | 4.82 | 5.65 | 5.75 |
| 1.050 | 23.7 | 5.08 | 5.96 | 6.17 |
| 1.075 | 24.2 | 5.27 | 6.26 | 6.40 |
| 1.100 | 24.8 | 5.40 | 6.44 | 6.64 |
| 1.125 | 25.3 | 5.75 | 6.64 | 7.01 |
| 1.150 | 25.9 | 6.28 | 6.95 | 7.41 |
| 1.175 | 26.5 | 6.64 | 7.41 | 7.70 |
| 1.200 | 27.1 | 7.14 | 7.70 | 8.00 |
| 1.225 | 27.7 | 7.41 | 8.42 | 8.32 |
| 1.250 | 28.4 | 7.70 | 9.13 | 8.84 |
| 1.275 | 29.1 | 8.32 | 9.81 | 9.48 |
| 1.300 | 29.8 | 9.02 | 10.30 | 10.02 |
| 1.325 | 30.6 | 9.40 | 11.23 | 10.72 |
| 1.350 | 31.4 | 10.72 | 11.95 | 11.78 |
| 1.375 | 32.4 | 12.07 | 13.00 | 12.69 |
| 1.400 | 33.3 | 13.47 | 13.47 | 14.32 |

Table 5b
5Ni-Cr-Mo-V Steel;
Stress Relieved; $\Delta\sigma$ = 2.74 ksi.

| Specimen Number: | | 860 | 861 | 862 |
|---|---|---|---|---|
| Thickness B (in.): | | 0.25 | 0.50 | 0.90 |
| Crack Length a (in.) | $\Delta K$ (ksi $\sqrt{in.}$) | da/dN × $10^{-6}$ | | |
| 0.825 | 30.8 | 9.25 | 10.23 | 10.48 |
| 0.850 | 31.4 | 9.76 | 10.48 | 10.86 |
| 0.875 | 32.1 | 10.48 | 10.94 | 11.45 |
| 0.900 | 32.8 | 10.86 | 11.66 | 12.28 |
| 0.925 | 33.4 | 11.26 | 12.28 | 12.72 |
| 0.950 | 34.2 | 12.07 | 12.63 | 13.17 |
| 0.975 | 35.0 | 12.50 | 13.12 | 13.64 |
| 1.000 | 35.8 | 12.94 | 13.54 | 14.12 |
| 1.025 | 36.5 | 13.41 | 14.38 | 14.64 |
| 1.050 | 37.3 | 14.38 | 14.90 | 15.44 |
| 1.075 | 38.2 | 14.90 | 15.44 | 16.00 |
| 1.100 | 39.0 | 15.44 | 16.17 | 16.89 |
| 1.125 | 39.8 | 16.78 | 17.52 | 17.40 |
| 1.150 | 40.8 | 17.21 | 18.53 | 17.58 |
| 1.175 | 41.8 | 18.53 | 19.24 | 17.92 |
| 1.200 | 42.7 | 19.62 | 20.08 | 18.67 |
| 1.225 | 43.7 | 20.96 | 21.65 | 19.24 |
| 1.250 | 44.8 | 22.55 | 22.55 | 10.81 |
| 1.275 | 45.8 | 23.81 | 23.51 | 22.09 |
| 1.300 | 47.0 | 24.53 | 24.53 | 23.50 |
| 1.325 | 48.2 | 26.21 | 26.21 | 25.07 |
| 1.350 | 49.5 | 29.44 | 28.74 | 26.81 |
| 1.375 | 50.9 | 30.94 | 30.94 | 28.08 |
| 1.400 | 52.4 | 32.56 | 32.56 | 31.74 |

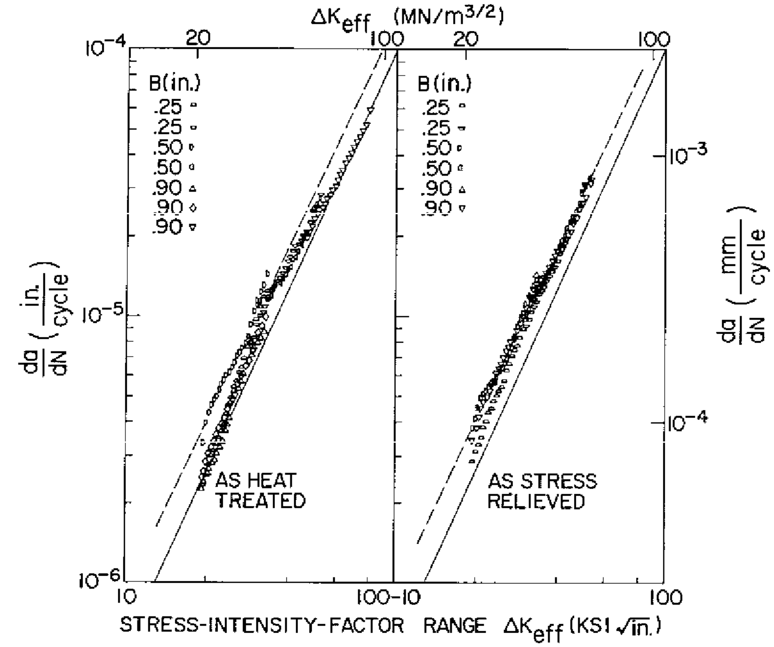



Fig. 2 — Crack-growth rate da/dN vs stress-intensity-factor range $\Delta K_{eff}$ for specimens of varied thickness. Data are for crack lengths of 0.825 to 1.400 in. (20.6 to 35.0 mm), comprising a/W values of 0.324 to 0.549. The solid line is the regression curve for 0.90-in. (22.5-mm) as-heat-treated specimens. The dashed line is the regression curve for three thicknesses of the stress-relieved material.

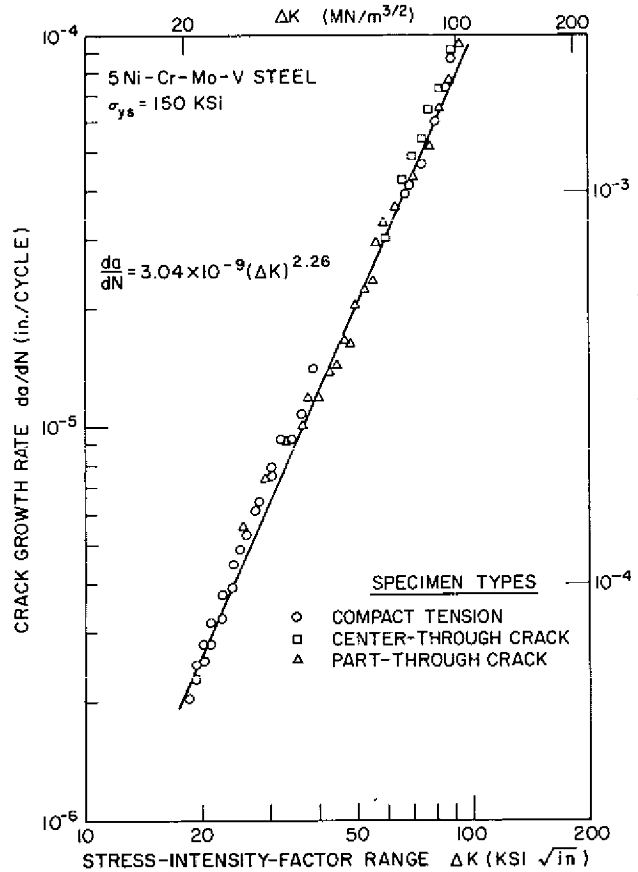



Fig. 3 — Crack-growth rate da/dN vs stress-intensity factor range ΔK for three specimen types. The trend line is for the 0.90-in. (22.5-mm) as-heat-treated material.

Several observations are apparent from an examination of Fig. 2. In both cases the data for the machined-down 0.25- and 0.50-in. (6.4- and 12.5-mm) thick specimens lie above the previously established trend line. Also, there is a good deal more scatter in the data from the machined-down as-heat-treated specimens then in that from the stress-relieved specimens. Finally, the more closely grouped data from the stress-relieved specimens lie above the reference trend line for all thicknesses tested, including the stress-relieved full-thickness 0.90-in. (22.5-mm) specimens. Details of the regression analysis for various groupings of the specimens are collected in Table 6. A regression-curve equation for all of the data from the stress-relieved specimens was calculated to be

$$\frac{da}{dN} = 5.94 \times 10^{-9} \Delta K_{eff}^{2.16}.$$

The correlation coefficient $r_{xy} = 0.99$ was obtained for this equation. Therefore, it would appear that there are no significant thickness effects, per se, in stress-relieved specimens of this material over the range of thicknesses studied; however, the stress-relieving heat treatment had the effect of nearly doubling the crack-growth rates.

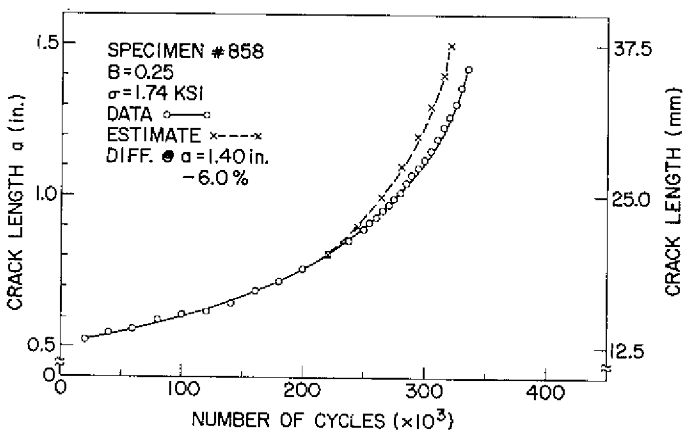
Table 6
Details of the Regression Analysis; $da/dN = A\ \Delta K^n$

| Specimen Number | Thickness (in.) | A ($10^{-9}$) | n | $r_{xy}$ |
|---|---|---|---|---|
| As Stress Relieved | | | | |
| Low Load | | | | |
| 858 | 0.25 | 0.92 | 2.70 | 0.997 |
| 863 | 0.50 | 4.71 | 2.24 | 0.991 |
| 859 | 0.90 | 2.76 | 2.40 | 0.996 |
| High Load | | | | |
| 860 | 0.25 | 2.90 | 2.36 | 0.998 |
| 861 | 0.50 | 5.74 | 2.19 | 0.998 |
| 862 | 0.90 | 15.58 | 1.91 | 0.994 |
| Low and High Loads | | | | |
| 858, 860 | 0.25 | 2.81 | 2.38 | 0.997 |
| 863, 861 | 0.50 | 8.81 | 2.07 | 0.996 |
| 859, 862 | 0.90 | 8.92 | 2.05 | 0.995 |
| All Six | N/A | 5.94 | 2.16 | 0.991 |
| As Heat Treated; Former Trendline | 0.90 | 3.04 | 2.26 | 1.000 |

Rockwell-C hardness measurements were made on all specimens before and after heat treatment, and no changes were detected. Therefore, it is unlikely that the stress-relieving heat induced any metallurgical change in the material, other than the intended effects. Rather, it is probable that the differences in crack-growth rates observed in the stress-relieved specimens resulted from relief of internal stresses. Previous attempts to section this material into thinner specimens of a configuration considerably longer and wider than the compact tension specimen resulted in substantial warpage, suggesting high levels of internal residual stress. Although classical mechanics theory requires that such internal stresses be "balanced" between tension and compression for the plate to be in equilibrium, it would be hazardous to assume that such "balanced" stresses do not affect the fatigue characteristics of the plate. For instance, residual compressive stresses are notoriously beneficial to fatigue resistance, and high levels of residual compressive stress are known to exist in rolled plate of the type tested. This is a possible explanation for the accelerated crack-growth rates observed in the stress-relieved specimens of all thicknesses studied (Fig. 2b).

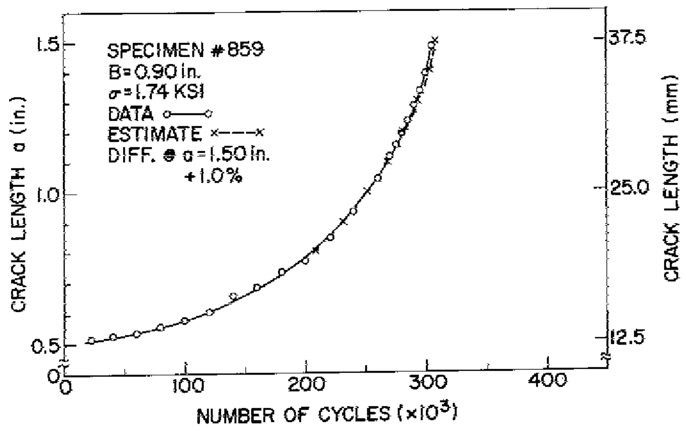
## ESTIMATES FROM REGRESSION ANALYSIS

The close correlation between the data curves of crack length a vs the number of cycles and the curves estimated from the regression equation is seen in Figs. 4 and 5. Comparison is made between the 0.25- and 0.90-in. (7.25- and 22.5-mm) specimens at both low and high stress levels, 1.74 and 2.74 ksi. Difference between the estimated and data curves ranged between +1.0 and − 6.0 percent.



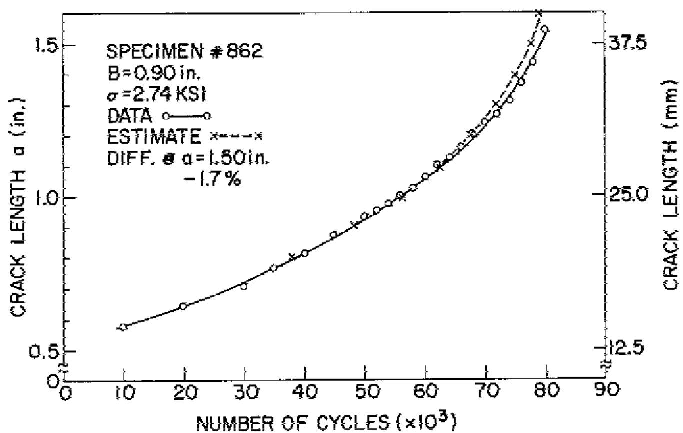

(a) Thickness B = 0.25 in. (6.25 mm)

Fig. 4 — Crack length a vs number of cycles. The data and estimated curves are for an applied stress of 1.74 ksi.

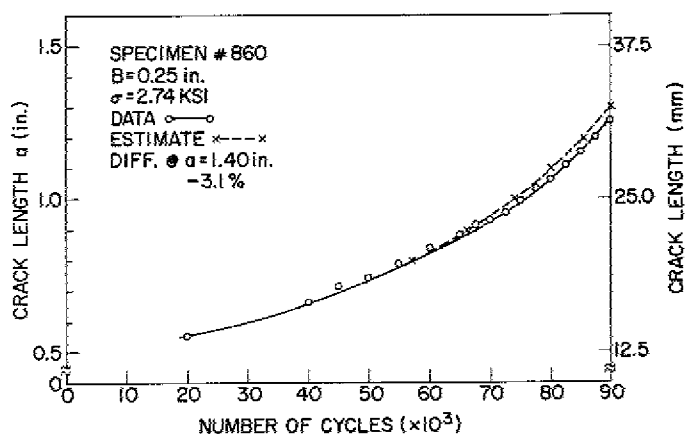



(b) Thickness B = 0.90 in. (22.5 mm)

Fig. 4 (continued) — Crack length a vs number of cycles. The data and estimated curves are for an applied stress of 1.74 ksi.




(a) Thickness B = 0.25 in. (6.25 mm)




(b) Thickness B = 0.90 in. (22.5 mm)

Fig. 5 — Crack length a vs number of cycles. The data and estimated curves are for an applied stress of 2.74 ksi.

Since it is not possible to integrate the da/dN expression (ΔK has to be evaluated in terms of a/W and the polynominal correction factor then raised by a fractional exponent), N was evaluated by summations of

$$\Delta N = \frac{\Delta a}{A \Delta K_{eff}^{n}} ,$$

the interval chosen for Δa being 0.100 in. (2.5 mm).

Inasmuch as the regression analysis covered only the region between 0.825 and 1.400 in. (20.625 and 35.0 mm), the values of ΔN were added to the number of cycles attained at 0.800 in. (20 mm) for each specimen.

## CONCLUSIONS

- No significant thickness effects, per se, on fatigue crack-growth rate were observed in stress-relieved compact tension specimens of 5Ni-Cr-Mo-V steel 0.25, 0.50, and 0.90 in. (6.4, 12.5, and 22.5 mm) in thickness.
- Crack-growth rates in the stress-relieved specimens were approximately double the crack-growth rates observed in as-heat-treated 0.90-in. (22.5-mm) thick specimens previously studied.
- Considerable scatter was apparent among crack-growth-rate data for as-heat-treated specimens machined down to thinner section sizes from 1.0-in. (25.4-mm) thick rolled plate.
- Curves of crack length vs the number cycles, estimated from the regression equation, agree well with the actual data curves.

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## REFERENCES

1. W.G. Clark, Jr., "Effect of Temperature and Section Size on Fatigue Crack Growth in Pressure Vessel Steel," Journal of Materials 6, No. 1, 134 (1971).
2. G.T. Hahn, R.G. Hoagland and A.R. Rosenfield, "Local Yielding Attending Fatigue Crack Growth," Air Force Systems Command, Aerospace Research Laboratories Report ARL 71-0234, Nov. 1971.
3. C.E. Richards and T.C. Lindley, "The Influence of Stress Intensity and Microstructure on Fatigue Crack Propagation in Ferritic Materials," Engineering Fracture Mechanics 4, 951 (1972).

4. J.R. Griffiths and C.E. Richards, "The Influence of Thickness on Fatigue Crack Propagation Rates in a Low Alloy Steel Weld Metal Above and Below General Yield," Materials Science and Engineering 11, 305 (1973).
5. J.M. Barsom, E.J. Imhof, and S.T. Rolfe, "Fatigue-Crack Propagation in High Yield-Strength Steels," Engineering Fracture Mechanics 2 301 (1971).
6. F. A. Heiser and W. Mortimer, "Effect of Thickness and Orientation on Fatigue Crack Growth Rate in 4340 Steel," Metallurgical Transactions 3, 2119 (1972).
7. W.G. Clark, Jr., and H.E. Trout, Jr., "Influence of Temperature and Section Size on Fatigue Crack Growth Behavior in Ni-Mo-V Alloy Steel," Engineering Fracture Mechanics (1970).
8. A.R. Jack and A.T. Price, "Effects of Thickness on Fatigue Crack Initiation and Growth in Notched Mild Steel Specimens," Acta Metallurgica 20, 857 (1972).
9. A.M. Sullivan and T.W. Crooker, "Analysis of Fatigue-Crack Growth in a High-Strength Steel — I. Stress Level and Stress Ratio Effects at Constant Amplitude," ASME Transactions (publication pending).
10. A.M. Sullivan and T.W. Crooker, "Evaluation of Fatigue Crack-Growth-Rate Determination Using a Crack-Opening-Displacement Technique for Crack-Length Measurement," NRL Report 7912, Sept. 1975.
11. W.G. Clark, Jr., and S.J. Hudak, Jr., "Variability in Fatigue Crack Growth Rate Testing," Journal of Testing and Materials, (publication pending).
12. R.J. Goode, "Identification of Fracture Plane Orientation," Materials Research and Standards 12, No. 9, 31 (1972).
13. A.M. Sullivan, "Crack-Length Determination for the Compact Tension Specimen Using a Crack-Opening Displacement Calibration," NRL Report 7888, June 1975.
14. E.T. Wessel, "State of the Art of the WOL Specimen for $K_{Ic}$ Fracture Toughness Testing," Engineering Fracture Mechanics 1, 77 (1968).