Fatigue-Crack Propagation Behavior of Several Pressure Vessel Steels and Weldments

Fatigue-crack growth rates in an air environment tend to increase with increasing test temperature, although—at a given temperature—there is very little difference in the crack growth of several PV steels from 75 to 800 F and only minor differences at 1000 F

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ABSTRACT. Linear-elastic fracture mechanics techniques were used to characterize the fatigue-crack growth behavior of four pressure vessel steels, plus weldments in two of these steels, over the temperature range 75-1000 F (24-538 C). Crack growth rates generally increased with increasing temperature, and the behavior of the four steels plus two weldments did not differ greatly from one another at a given temperature.

The effects of several parameters upon crack growth behavior in pressure vessel steels are also reviewed.

Introduction

Fatigue damage to pressure vessels can be thought of as occurring in two different stages: crack initiation, and crack propagation. However, in conducting fatigue analyses on pressure vessel and piping components, it is often conservative to ignore the crack initiation process, assume that the component already contains a preexisting crack or defect, and use the analysis technique of fracture mechanics to estimate the in-service extension of the defect. Examples of this process are given in the literature.[1,2]

Hypothesizing the existence of an initial crack or defect seems especially appropriate for the case of large welded structures such as pressure vessels and piping systems since the welds may contain defects (microfissures, lack of fusion, voids, inclusions, etc.). Hence, characterization of the crack extension properties of these materials in terms of fracture mechanics parameters can be quite useful.

One objective of this paper is to describe the effect of temperature upon the fatigue-crack growth behavior of several pressure vessel steels and weldments. Another is to review recent data on the effects of several parameters upon crack growth behavior of these materials.

Experimental Procedure

Four pressure vessel steels (ASME SA-387 Grades C and D,* SA-516 Grade 60, and SA-533 Grade B class 1) were studied, plus weldments in two of these steels. The four wrought steels plus two filler metals are designated as materials A through F, and the identification of these materials is given in Table 1. The chemical analyses and mechanical properties of these materials are detailed in Tables 2 and 3, respectively.

The tensile specimens for materials E and F were obtained from the as-deposited weld metal and were oriented longitudinally with respect to the direction of welding. Additional tensile and fracture toughness results on the same heats of material as materials C and D may be found in the literature.[3,4] The Nil-Ductility Transition Temperatures (NDTT) of materials A through D are 40 F (4 C), −10 F (−23 C), −40 F (−40 C)[3] and 10 F (−12 C),[5] respectively.

Two different weldments were utilized in this study; these are designated as type 1 and type 2. Type 1 welds were produced using an automatic submerged-arc process. The base metal was material A and the filler metal was material E (2¼ Cr-1 Mo). Type 1 weldments were given a postweld stress relieving treatment of 12 h at 1300 F (704 C) followed by an air cool. The Type 1 weld is illustrated in Fig. 1.

Type 2 welds were also produced using a submerged-arc process. The base metal was material C and the filler metal was material F (AWS E8018-C1). The Type 2 weld is illustrated in Fig. 2.

Both types of weldment specimens were oriented such that the crack was parallel to the welding direction, and the crack was placed in the center of the fusion zone. According to the crack orientation system described previously,[6] these cracks would have a "BA" orientation.

ASTM "Compact Specimens"[7] were utilized in the crack growth tests. The specimens had a nominal width (w) of 2.00 in. (50.8 mm), and the thickness (B) ranged between 0.45 in. (11.4 mm) and 0.5 in. (12.7 mm). The specimens were tested on a feedback-controlled MTS testing machine using load as the control parameter. A stress ratio ($R = K_{min}/K_{max}$) of 0.05 and sinusoidal

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*SA-387 grade C is equivalent to SA-387 Grade 11 class 1 steel, and SA-387 grade D is equivalent to SA-387 Grade 22 class 1 steel.

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waveform were employed for all tests. Tests at elevated temperatures were conducted in an air-circulating furnace at a cyclic frequency (f) of 40 cpm (0.667 Hz). Since frequency would not be expected to be an important variable at room temperature,[8] room temperature crack growth tests were conducted at frequencies ranging between 180 and 600 cpm (3–10 Hz).

Crack lengths were determined periodically throughout each test using a travelling microscope. Fatigue-crack growth rates (da/dN) were determined by dividing each increment of crack extension by the number of cycles producing that increment. The stress intensity factor (K) was calculated by formula[7] and was based on the average crack length in a given increment. The results were then plotted as log (da/dN) as a function of log (ΔK).

Results and Discussion

Fatigue-crack growth tests were conducted at temperatures of 75 F (24 C), 600 F (316 C), 800 F (427 C) and 1000 F (538 C); the results for base metal specimens are shown in Figs. 3–6, and for weldment specimens in Figs. 7–10. The results for specimens 383 (material

Table 1—Material Identification

Material	Producer/ heat no.	Product form	Material condition
A	U. S. Steel/1P4255	3 in. plate SA-387, Gr. C.	Mill annealed.
B	Lukens/B8238	3-1/2 in. plate SA-387, Gr. D.	Annealed per specification RDT M5-5T[b]
C	unknown/802B06530	1 in. plate SA-516, Gr. 60	Mill annealed.
D	Lukens/A-1195-1[a]	12 in. plate SA-533, Gr. B, Cl. 1	Quenched & tempered.
E	RACO/2P5022	Weld filler metal, RACO 521S	Auto. sub. arc welded. Stress relieved 12 h @ 1300 F (704 C), A.C.
F	unknown	Weld filler metal, AWS E8018-C1	Sub. arc welded. Tested as-welded.

[a] Heavy Section Steel Technology Program Plate No. 02.

[b] 1700 F (927 C) for 1 h per inch of thickness; cool to 600 F (316 C) at rate not exceeding 100 F/h (55.5 C/h); cool to room temperature in still air.

Table 2—Chemical Composition, wt-%

Material	C	Mn	P	S	Si	Cr	Mo	Ni	Cu	V	Sn	Al	Ti
A	0.15	0.56	0.016	0.013	0.91	1.35	0.52	0.06	0.05	0.006	0.009	0.020	0.01
B	0.12	0.50	0.010	0.020	0.22	2.30	0.98	0.1	(a)	(a)	(a)	(a)	(a)
C	0.15	1.20	0.005	0.025	0.23	0.005	0.01	0.008	0.020	(a)	0.001	0.052	(a)
D	0.22	1.48	0.012	0.018	0.25	(a)	0.52	0.68	(a)	(a)	(a)	(a)	(a)
E[b]	0.09	0.80	0.021	0.019	0.52	2.41	0.97	0.22	0.27	0.01	0.014	0.19	0.01
F[b]	0.08	1.12	0.017	0.021	0.45	0.02	0.01	1.50	0.02	0.012	0.001	0.003	(a)

[a] Not determined.

[b] As-deposited.

Fig. 1—Macrophotograph of type 1 weld; nital etch

Fig. 2—Macrophotograph of type 2 weld; nital etch

Table 3—Mechanical Properties[a]

Material	Specimen no.	Test temp., F	0.2% offset yield, psi	Ultimate strength, psi	Uniform elong.,[b] %	Total elong., %	Reduction in area,[b] %	Hardness,[b] R_b	Site sequence no.[d]
A	T217	75	36,200[c]	67,360	15.59	22.55%	61.16%	77.02	H03000
A	T218	600	31,650	69,090	10.89	16.00	65.29	N.D.	H03003
A	T219	800	29,100	59,020	9.32	18.26	68.85	N.D.	H03004
A	T220	1000	24,920	40,000	9.50	37.99	87.70	N.D.	H03005
B	T470	75	35,850	71,460	13.31	20.13	59.35	78.80	H03001
B	T471	600	41,220	77,400	10.33	14.35	50.41	N.D.	H03002
B	T472	800	32,930	68,780	9.60	15.45	56.91	N.D.	H03006
B	T473	1000	31,220	55,120	13.14	28.33	69.92	N.D.	H03007
C	T475	75	39,520	65,400	18.90	27.26	75.81	75.47	H03300
C	T476	600	33,740	69,270	16.45	28.75	76.42	N.D.	H03301
C	T477	800	29,670	46,910	11.27	30.33	85.37	N.D.	H03302
C	T478	1000	19,670	24,750	7.74	65.30	88.52	N.D.	H03303
D	–	75	67,500[c]	86,500	N.D.	17.50	N.D.	89.62	See Hunter *et al*[4]
D	–	575	55,300	80,800	N.D.	17.40	N.D.	N.D.	See Hunter *et al*[4]
E	T180	75	65,530[c]	82,760	10.55	18.22	65.85	90.50	H03200
E	T181	600	57,850	79,830	6.96	12.63	61.98	N.D.	H03201
E	T182	800	58,940	73,010	6.05	14.54	67.48	N.D.	H03202
E	T183	1000	50,490	53,410	1.20	22.20	78.86	N.D.	H03203
F	T485	75	79,590[c]	89,430	7.33	14.24	71.54	94.10	H03304
F	T486	600	73,770	99,590	11.44	17.32	60.66	N.D.	H03305
F	T487	800	62,950	76,070	6.00	11.99	38.52	N.D.	H03306
F	T488	1000	40,890	41,460	0.56	28.77	86.18	N.D.	H03307

[a] Strain rate = 3×10^{-3} sec^{-1} (except for material D where $6.67 \times 10^{-5} < \epsilon < 1.33 \times 10^{-4}$ sec^{-1}).

[b] N.D. = not determined.

[c] Upper yield strength.

[d] HEDL LMFBR Fuel Cladding Information Center.

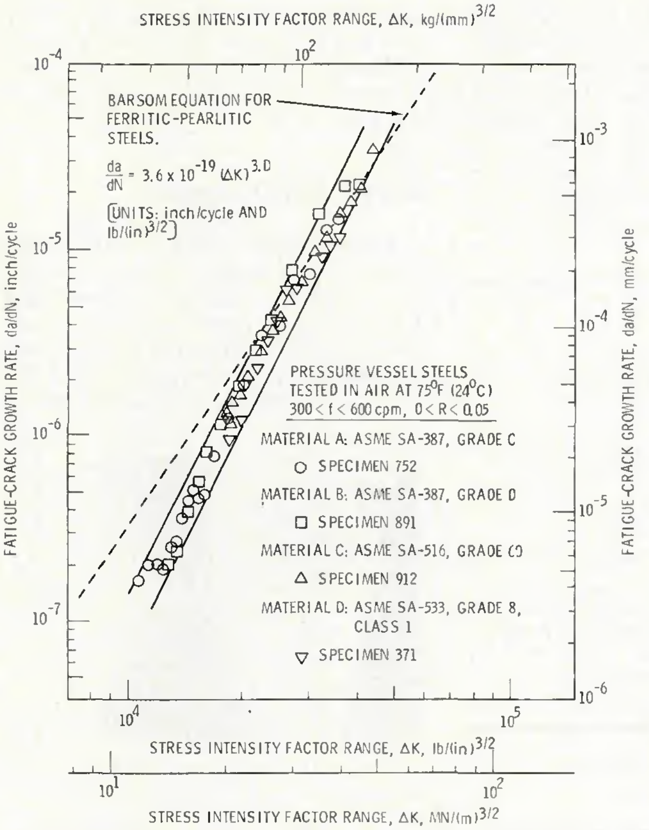

Fig. 3—Fatigue-crack growth behavior of four ferritic pressure vessel steels tested in an air environment at 75 F (24 C)

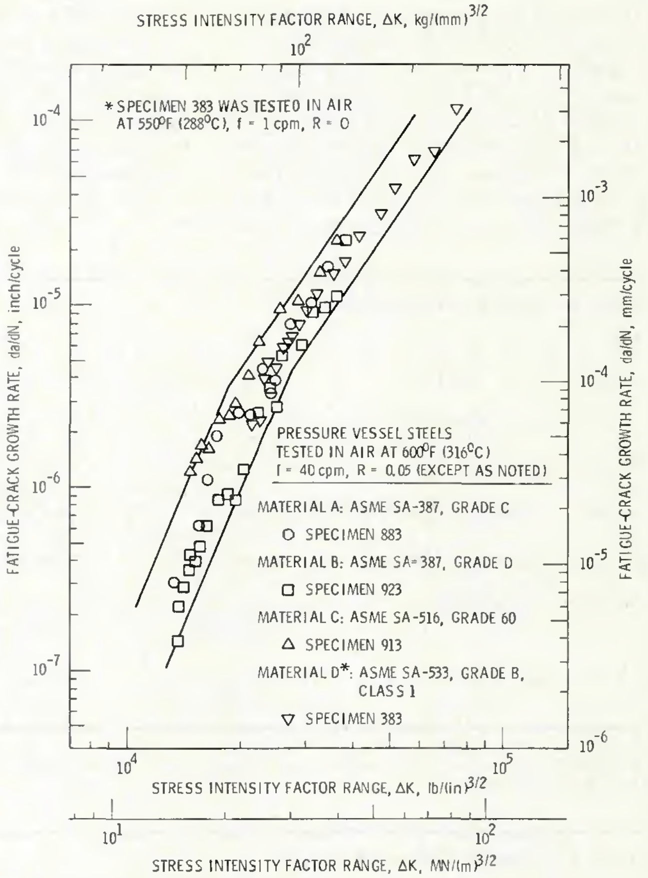

Fig. 4—Fatigue-crack growth behavior of four ferritic pressure vessel steels tested in an air environment at 600 F (316 C)

D) and 371 had been previously reported.[8,9]

Comparing the crack growth results for the different pressure vessel steels at a given test temperature in Figs. 3-6 shows that, up to a temperature of 800 F (427 C), all the steels behave in a similar fashion. This is in agreement with the observations of Hickerson *et al*[10] and Barsom[11] that fatigue-crack growth behavior in the different grades of low-alloy pressure vessel steels does not differ significantly from one alloy to another.

Figure 3 compares the results of the present study, and the equation proposed by Barsom[11] for the behavior of ferritic-pearlitic steels at room temperature. In general, the agreement is good. The room temperature results for material C are also in good agreement with the room temperature results reported by Sullivan and Crooker[12] for the same alloy. Also, although comparisons are not shown here, reasonably good agreement between the present results on materials B and D, and those of Brinkman *et al*[13] and Paris *et al*,[14] respectively, for the same grades of alloys is obtained where test temperatures, stress ratios, and cyclic frequencies.

As seen in Fig. 6, at a test temperature of 1000 F (538 C) there is some difference in the crack growth behavior of the three steels that were tested. Least-squares-regression lines are drawn through the data for each material, and it will be seen that material C (SA-516 gr. 60) exhibits the highest growth rates, followed by material A (SA-387 gr. C), with material B (SA-387 gr. D) exhibiting the lowest growth rates. It should be noted that this temperature is near the upper end of the temperature range where these alloys are normally utilized.

Comparing the curves for each of the different test temperatures in Figs. 3-6 shows that, in general, fatigue-crack growth rates increase with increasing temperature. This is in agreement with similar observations on the effect of temperature upon the crack growth behavior of other pressure vessel steels tested in an air environment[13,15,16] as well as observations on other alloys such as austenitic stainless steels.[17]

Comparing the results for the weldment specimens (Figs. 7-10) with those for base metal specimens tested at the same temperatures shows that, in general, the behavior is quite similar, both between the two types of weldments themselves as well as between the weldments and base metals. There is some difference in the behavior of the weldment specimens at room temperature, but the differences tend to disappear as the temperature is increased.

Comparisons between base metals and weldments in pressure vessel steels have been made in previous studies,[18-26] usually at room temperature; in general, it has been observed that crack growth rates in weldments are equal to, or somewhat lower than, those in base metal. Similar observations have been made for weldments in austenitic stainless steels at elevated temperatures.[6,27,28] In some cases where crack growth rates have been lower in the weldments, the reduction in crack growth rates has been attributed to compressive residual stresses.[22,24,28]

Fatigue-crack growth behavior is often expressed in the form:

$$\frac{da}{dN} = C\ (\Delta K)^n$$

where "C" and "n" are dependent upon the material as well as other parameters such as temperature, cyclic frequency, environment, stress ratio, etc. Comparing the behavior of both the base metal and weldment specimens as the test temperature is increased, it will be noted that there is some tendency for the exponent "n" (i.e., the slope of the log (da/dN) vs. log (ΔK) curves) to decrease with increasing temperature.

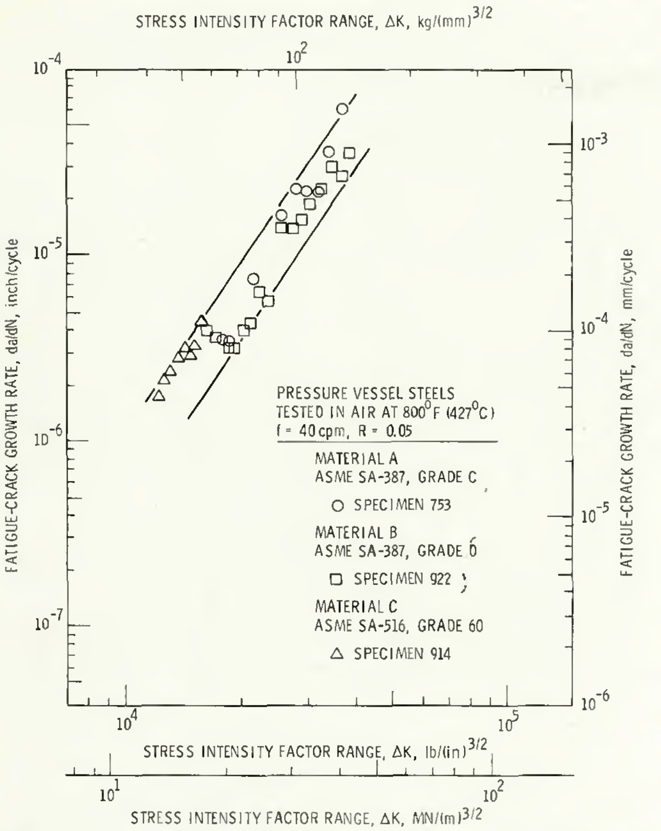

Fig. 5—Fatigue-crack growth behavior of three ferritic pressure vessel steels tested in an air environment at 800 F (427 C)

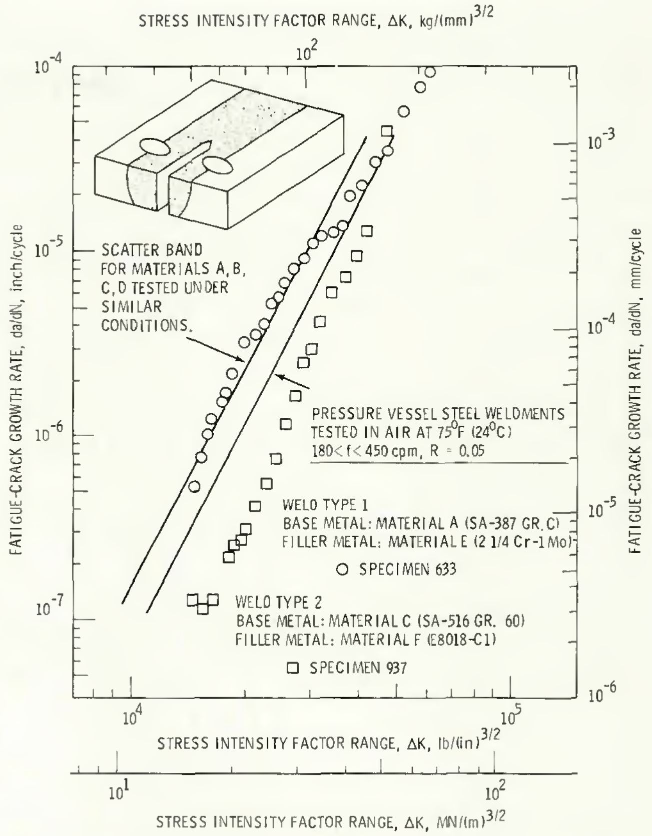

Fig. 7—Fatigue-crack growth behavior of pressure vessel steel weldments tested in an air environment at 75 F (24 C)

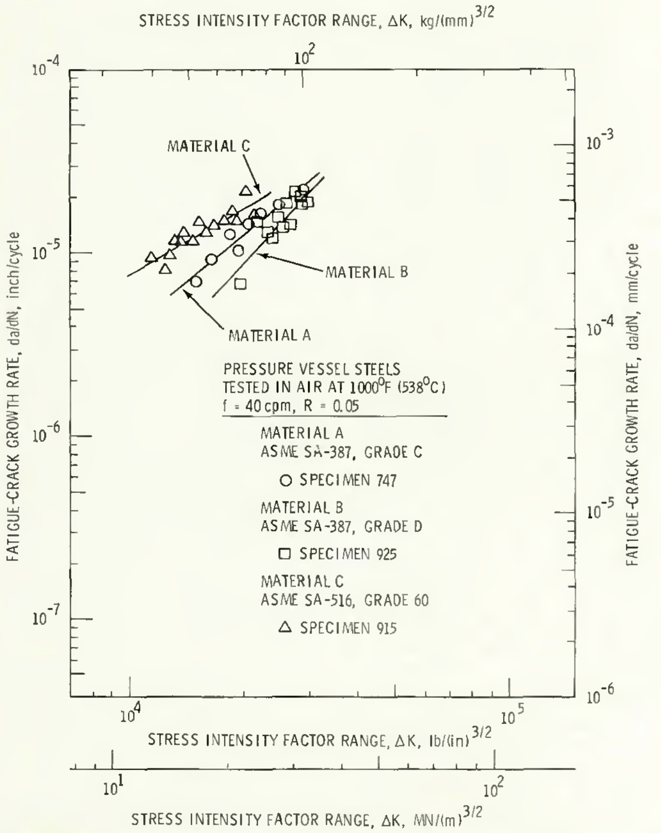

Fig. 6—Fatigue-crack growth behavior of three ferritic pressure vessel steels tested in an air environment at 1000 F (538 C)

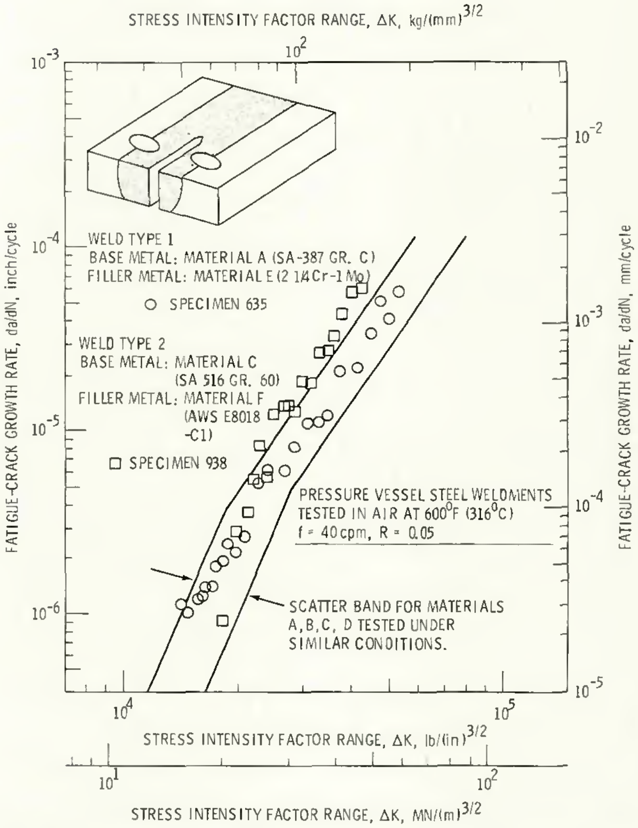

Fig. 8—Fatigue-crack growth behavior of pressure vessel steel weldments tested in an air environment at 600 F (316 C)

A number of parameters have been shown to influence the crack growth behavior of pressure vessel steels. It is appropriate to briefly review the results here. The effect of cyclic frequency has been studied by a number of investigators and appears to be closely related to the test temperature and environment. For example, cyclic frequency had little effect in an air environment upon the crack growth behavior of SA-533 Grade B at 550 F (288 C),[8] a minor detrimental effect (i.e., increased growth rates with decreasing frequency) upon the behavior of A-212B (equivalent to SA-516 grade 70) at 600-650 F (316-343 C)[29] and a noticeable effect upon the behavior 9Ni-4Co-0.3C steel at 950 F (510 C).[15] Frequency has also been observed to have a similar effect upon the behavior of SA-387 Grade 22 class 1 steel (equivalent to SA-387 Grade D) at temperatures of 950 F (510 C) and 1100 F (593 C) in an air environment.[13]

Frequency can also have an effect in environments such as pressurized water at elevated temperatures[30-33] or high temperature steam,[34] but the frequency effects noted are generally no more severe than in an air environment at the same temperature. The surrounding environment can have a significant effect upon crack growth behavior depending upon the temperature, frequency, stress ratio, and—of course—the environment, itself. For example, pressurized water at an elevated temperature generally produces crack growth rates somewhat higher than in an air environment at the same temperature,[30-33] while high-temperature steam produces slightly lower growth rates.[34] Elevated temperature helium[34] and liquid sodium[35] environments, on the other hand, produce crack growth rates significantly lower than in an air environment at the same temperature.

The stress ratio ($R = K_{min}/K_{max}$) has been shown to have an effect upon fatigue-crack growth behavior of pressure vessel steels, with crack growth rates (at a given value of ΔK) generally increasing with increasing values of R.[13,29,36]

The effect of neutron irradiation has been studied in several pressure vessel steels and weldments,[8,9,37,38] and, in general, little or no effect has been noted. Where effects have been noted, crack growth rates generally tend to decrease slightly with neutron irradiation.

Metallurgical variables generally tend to have little or no effect upon crack growth behavior in pressure vessel steels; this result is apparent from the similar behavior exhibited by the different steels in this study as well as those in other studies.[10,11] Crack orientation has been shown to have a minor effect on crack growth behavior in hot-rolled plate.[39] On the other hand, grain size[40] and section thickness[12,41] have been shown to have no effect.

Summary

The results of this study may be summarized as follows:

1. In general, fatigue-crack growth rates in an air environment tend to increase with increasing test temperature.
2. Very little difference exists (at a given temperature) in the crack growth behavior of several pressure vessel steels over the range of 75-800 F (24-427 C), and only minor differences appear to exist at a temperature of 1000 F (538 C).
3. Fatigue-crack growth rates in plate material and in weldments are generally similar for similar test conditions.
4. The effect of several parameters upon fatigue-crack growth behavior in pressure vessel steels was reviewed. Temperature, cyclic frequency, environment, and stress ratio were shown to have an effect under certain conditions. On the other hand, neutron irradiation and metallurgical variables were shown to have little or no effect.

Acknowledgments

This paper is based on work

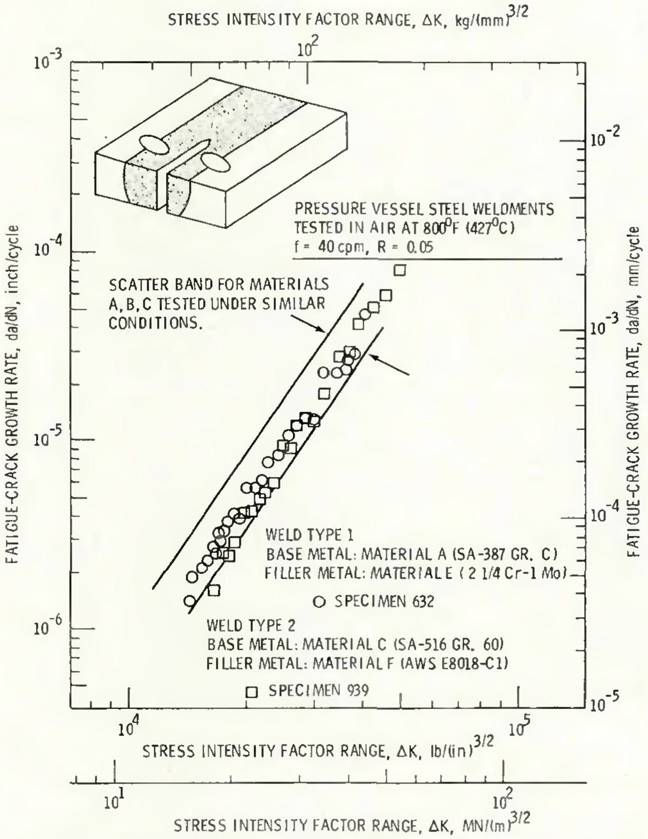

Fig. 9—Fatigue-crack growth behavior of pressure vessel steel weldments tested in an air environment at 800 F (427 C)

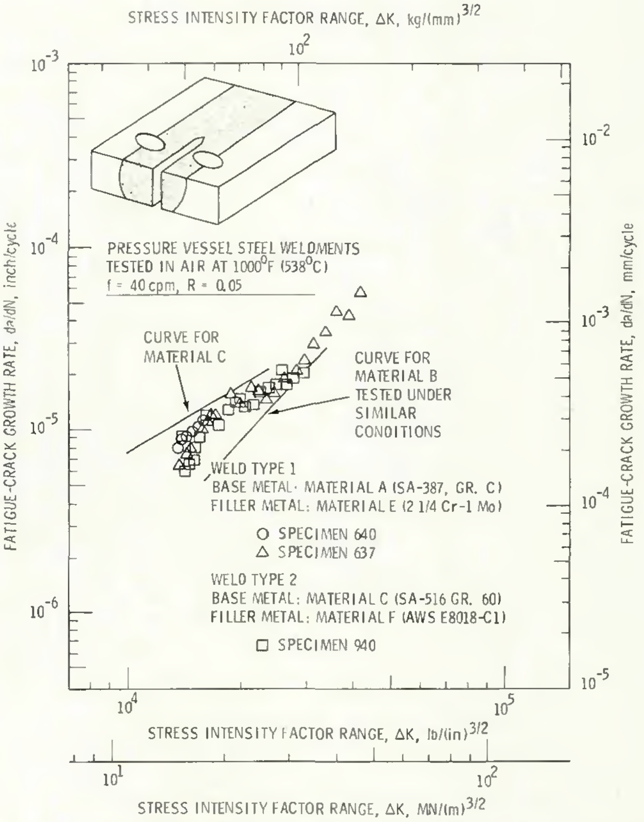

Fig. 10—Fatigue-crack growth behavior of pressure vessel steel weldments tested in an air environment at 1000 F (538 C)

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WRC Bulletin 229

August 1977

(1) Dynamic Fracture-Resistance Testing and Methods for Structural Analysis

by E. A. Lange

The potential for the initiation of fast fracture can be predicted by the recently developed technology of linear elastic fracture mechanics (LEFM) which has produced the basis for an analytical approach to fracture resistance and structural integrity. To make fracture mechanics a viable engineering design tool, empirical correlations between practical dynamic test results and the basic parameters are needed. In this paper the attributes and limitations of the Charpy, Drop Weight-Nil Ductility Transition Temperature, Drop Weight Tear, and Dynamic Tear tests are discussed with respect to providing information useful in structural integrity analyses.

(2) Junction Stresses for a Conical Section Joining Cylinders of Different Diameter Subject to Internal Pressure

by W. J. Graff

The conical transition section of a cylindrical pressure vessel was instrumented inside and outside with electric resistance strain gages, and from the longitudinal and circumferential strains measured experimentally, the corresponding stresses were determined. The results were compared with calculated stresses from the theory of shells. The experimentally determined stresses exceeded code membrane stresses in the immediate vicinity of the junctions.

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WRC Bulletin 221

November 1976

Analysis of Test Data on PVRC Specification No. 3, Ultrasonic Examination of Forgings, Revision I and II

by R. A. Buchanan

The purpose of this report is to review, analyze and draw conclusions from data developed during efforts to test the validity of the procedures allowed by PVRC Specification No. 3, Revisions I and II. The author states that the only way to reduce the variation in test data from one group to another would be to restrict the procedures of PVRC Specification No. 3 so that only certain equipment combinations or, if practical, only one combination could be used.

Analysis of the Nondestructive Examination of PVRC Plate-Weld Specimen 251J—Part A

by R. A. Buchanan

During the fabrication of PVRC plate-weld specimen 251J, 15 welding defects were deliberately introduced. After fabrication, the specimen was ultrasonically examined for welding defects by a number of different company teams. The teams conducted their tests independently and had no knowledge of the types or locations of the intentional defects. Two different PVRC procedures for ultrasonic examination were followed by the teams in their evaluation of the specimen.

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