The Effect of Welding on the Fatigue Crack Growth Rate in a Structural Steel

Poor steelmaking practices and non-low-hydrogen electrodes were found to accelerate fatigue cracking

BY G. O. RADING

ABSTRACT. Fracture mechanics principles have been used to study the effects of welding on the rate of fatigue crack growth (FCG) in a low-carbon structural steel. The steel concerned is used widely in the fabrication of the structural framework of passenger buses. Tests were carried out on the base metal (BM), heat affected zone (HAZ) and weld metal (WM). Both the near threshold and midrange regimes of crack growth were studied. In the midrange regime, the FCG rate was highest in the HAZ and lowest in the WM. Near the threshold, the FCG rate was highest in the BM and lowest in the WM. The results are explained in terms of microstructural changes due to welding, welding residual stresses, and fracture mechanisms. Recommendations to reduce the incidence of fatigue cracking have been made.

Introduction

Most of the structural steel that is currently used in Kenya is cast and rolled locally. The bulk of the raw material consists of an assortment of steel and cast iron scrap that is arc melted and then rolled. Manufacturers who build passenger buses use this material to fabricate the structural framework. The operators of the said buses reported a high incidence of fatigue failures. On examination, it was revealed that most of the fatigue cracks occurred in the heat-affected zone (HAZ). Figure 1 shows the extent of cracking in one such bus as it was brought in for repairs.

Investigation of the melting practices and mill procedures indicated several weaknesses with regard to quality control. There was little control of the quality of scrap, no attempts to degas the melt, no close control of the chemistry, little control of temperature during rolling and contact of hot metal with water during rolling.

The purpose of this investigation was to study the effects that welding has on fatigue crack growth in this material. In particular, to study the rate of fatigue crack growth in the base metal (BM), heat-affected zone (HAZ) and weld metal (WM). The investigation covered both midrange (where the Paris law is applicable) and near threshold (below a crack growth rate of approximately 3 X 10^{-6} mm/cycle) regimes of FCG.

KEY WORDS

Effects of Welding
Low-C Structural Steel
Fatigue Crack Growth
Base Metal
Heat-Affected Zone
Weld Metal
Microstructure Changes
Residual Stresses
Fracture Mechanics
Mechanical Properties

G. O. RADING is a Graduate Research Assistant in the Department of Metallurgical and Materials Engineering, University of Alabama, Tuscaloosa, Ala., presently on leave from Moi University, Kenya, Africa.

Materials and Test Procedures

The material studied is a low-carbon structural steel. The chemical composition and mechanical properties are given in Table 1, which also includes the requirements of ISO 630 (Ref. 1) for this grade of steel.

The fatigue crack propagation tests were performed on center cracked tension specimens. The dimensions of the specimens are shown in Fig. 2. The thickness of the specimen is the same as that used in the fabrication of the bus body frameworks (about 2 mm.). To assess the rate of FCG in the weld metal, the material was cut into two and rewelded. The center notch was then machined such that the crack would grow along the WM. To preserve the thickness, the

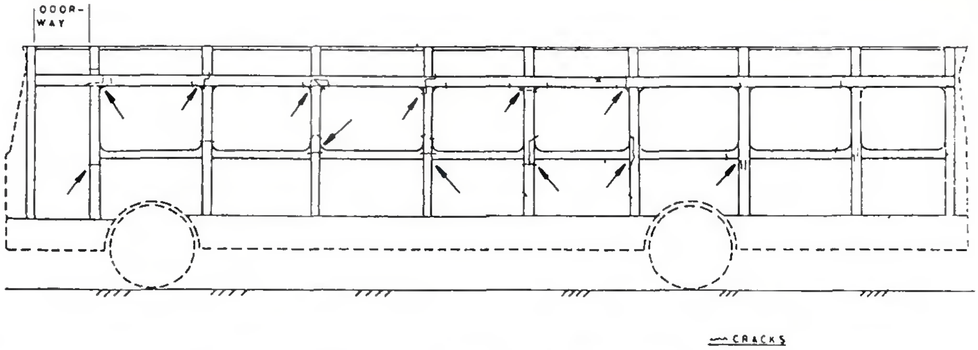

Fig. 1 — The extent of cracking in a vehicle framework brought in for repairs The arrows indicate positions of the cracks.

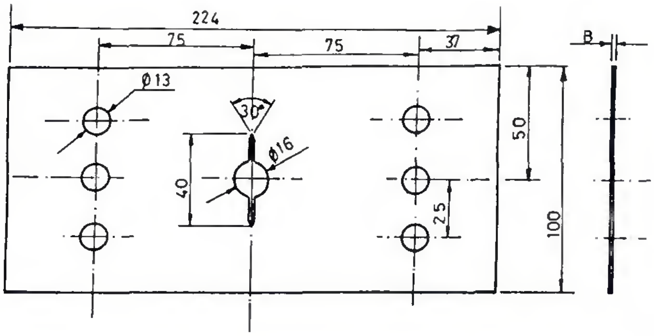

Fig. 2 — Dimensions of the specimen.

weld bead was ground flush. Specimens for testing FCG in the HAZ were similarly prepared, but the notch was machined adjacent to the weld to make the crack grow along the HAZ (parallel to the weld). The position of the notch relative to the weld was determined by prior macro-etching of a similar weld.

The tests were performed on a rig designed for this purpose. The load was measured by a strain gauge based load cell attached to an oscilloscope. The stress intensity factor was calculated from (Refs. 2, 3)

$$\Delta K = \frac{\Delta P}{B}\sqrt{\frac{\pi\alpha}{2W}\sec\frac{\pi\alpha}{2}} \qquad (1)$$

where, $\alpha = 2a/W$, and ΔP is the alternating load. The crack length was measured using a traveling microscope accurate to 0.1 mm. The crack growth rate, da/dN, was then calculated (determined) using the following two methods:

1) In the midrange regime (regime II), a graphical method was used, *i.e.*, a graph of a vs. N was plotted and the gradient determined at various points.

2) Near the threshold, the secant method was used, *i.e.*, da/dN was determined from

$$\left[\frac{da}{dN}\right]_a = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \qquad (2)$$

where $a = ½ (a_{i+1} + a_i)$, and the subscript, i, denotes the i'th data point.

All tests were performed at an R-ratio of 0.2 and a frequency of 24 Hz in laboratory air. All the midrange tests were performed at a constant ΔP in accordance with the ASTM standard (Ref. 3), while near the threshold, the decreasing K technique, (Ref. 3), was used. In all cases, precracking was carried out under the same conditions (frequency, R-ratio, environment, maximum load, etc.) as the actual test, following the procedures in ASTM 647 (Ref. 3).

Results

The midrange FCG curves for the base metal, weld metal, and heat-affected zone are shown in Figs. 3, 4, and 5, respectively. The graphs show the range of stress intensity calculated from Equation 1 plotted against da/dN determined by the graphical method as explained earlier. The results are seen to follow the Paris law

$$\frac{da}{dN} = C\Delta K^m \qquad (3)$$

For ΔK in MPa $m^{1/2}$ and da/dN in mm/cycle, the values of C and m determined were as shown in Table 2.

Figure 6 shows the results of the near threshold FCG tests for the BM, HAZ and WM. In this regime, the Paris equation is no longer applicable. In Fig. 7, all the results are plotted together on the same diagram.

Figures 3 to 7 show the following trend in FCG for this material:

1) In regime II of FCG, the rate is highest in the HAZ and lowest in the WM. The difference between the rates in the HAZ and BM diminishes at low values of stress intensity range (exemplified by the difference in the exponent, m).

2) Still in the midrange, the difference between the FCG rates in the BM and WM is highest at low values of stress intensity range, the difference diminishes at higher values of stress intensity range.

3) Near the threshold, the FCG rate is highest in the BM and lowest in the WM. There is thus a cross-over in the FCG curves pertaining to the BM and that pertaining to the HAZ.

Discussion

Weld Metal

The results given above show that the rate of FCG is lowest in the weld metal. This is so both in the mid-range and near threshold regimes. There are several factors which contribute to this.

Residual Stresses

The welding process leaves behind stresses distributed as shown in Fig. 8

Table 1 — The Chemical and Mechanical Properties of the Material Tested.

	Yield Stress (MPa)	UTS (MPa)	Elong. (%)	C (%)	Mn (%)	S (%)	P (%)	N (%)
Material	290	370	26	0.12	0.49	0.009	0.006	0.04
ISO	270	430-	22	0.24	1.6	0.05	0.06	0.009
630	min.	530	min.	max.	max.	max.	max.	max.

Table 2 — Summary of Mid-range FCG Results

	m	C
BM	3.6	$1.35 * 10^{-9}$
HAZ	4.3	$2.9 * 10^{-10}$
WM	4.8	$1.6 * 10^{-11}$

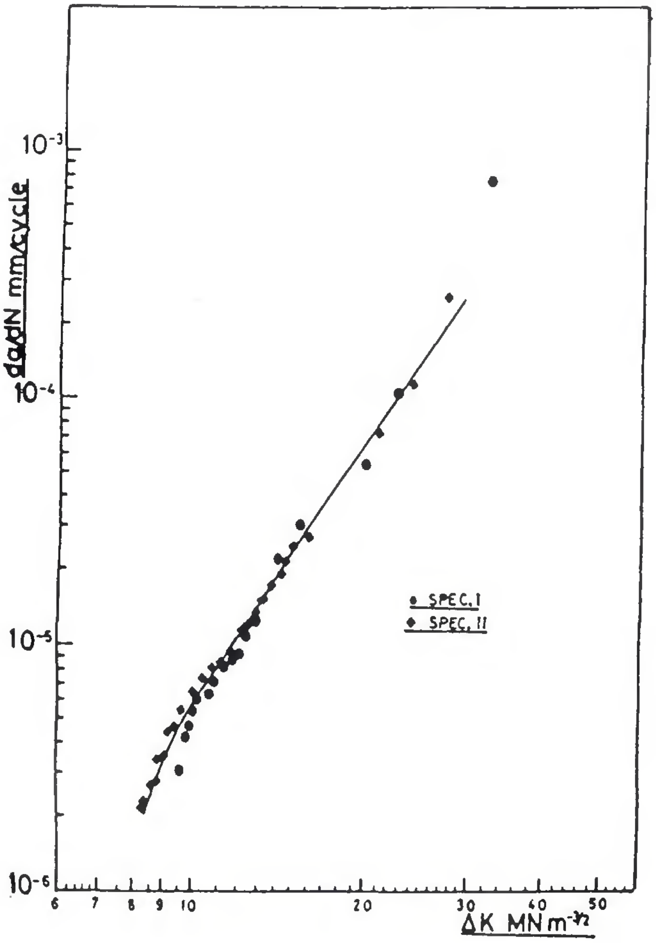

Fig. 3 — Midrange FCG rate data for the base metal.

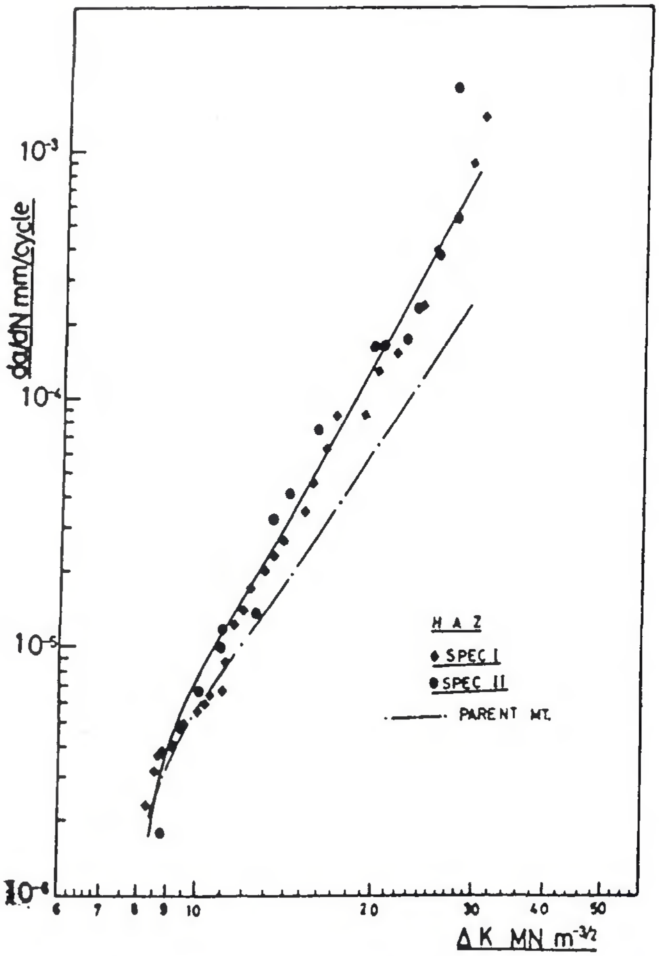

Fig. 4 — Midrange FCG rate data for the HAZ.

(Ref. 4). These stresses may be as high as the yield stress (Ref. 5). For a thin plate, such as the one tested here, the stresses can be taken as uniform through the thickness. No appreciable tunneling was evident. As can be seen from Fig. 10, the residual stresses are compressive in the part of the specimen where the crack is growing, and will result in a reduction of stress intensity such that

$$\Delta K_{eff.} = \Delta K - K_{res.} \quad (4)$$

where $K_{res.}$ is the stress intensity due to the compressive stress[1]. Figure 8 shows a reduction in the magnitude of the compressive stress as the distance from the center of the plate increases. Thus, the contribution of $K_{res.}$ should decrease at higher values of stress intensity. This is indeed what is observed in Fig. 5.

A similar trend has been observed by several workers (Refs. 6–12), and some of the workers have shown that when the residual stresses are relieved, the rates of FCG though the BM and WM become essentially the same (Refs. 6, 7, 8, 12, 13).

Weld Micro-Imperfections and Crack Tip Morphology

Small, rounded micro-imperfections like porosity, slag inclusion, etc., (but excluding weld microcracks) will result in crack tip blunting. This reduces the sharpness of the crack and, hence, the effective value of stress intensity, resulting in a lower FCG rate. Furthermore, it may be necessary for the crack to re-initiate or the nature of the imperfection may lead to crack tip kinking and branching. All these factors lead to a reduced effective stress intensity and, hence, a lower FCG rate. A similar reasoning was advanced by Maddox (Ref. 14).

However, the beneficial effects of micro-imperfections are likely only if their size and number are below some critical value. This critical value depends on the number of stress cycles required to re-initiate the crack, compared to the number of cycles required to grow the crack through sound material by an amount equal to the diameter of the defect. This number of cycles can be estimated by integrating Equation 3 and using the values of C and m from Table 2. It is expected that a suitable nondestructive test would detect those imperfections that exceed the critical size.

Changes in Microstructure and Mechanical Properties

The mechanical properties and microstructure of the weld metal are dif-

1. The equation does not invoke crack closure arguments. K_{res} is calculated from residual stress at each point, *i.e.*, $K_{res} = f(\sigma_{res}) = f(a)$, and this value is then substracted from the mechanically applied stress intensity. Crack closure can occur without residual stress (*e.g.*, oxide induced closure or mode II induced displacement). Conversely, residual stresses can occur without crack closure. For example, if the residual stresses are tensile, Equation 4 is still applicable, except that K_{res} is added rather than subtracted. But tensile residual stresses do not cause crack closure. This also clarifies the point concerning the equations' range of applicability. Where there is no residual stress, K_{res} is set to zero. Where the stress is tensile, K_{res} is added rather than subtracted.

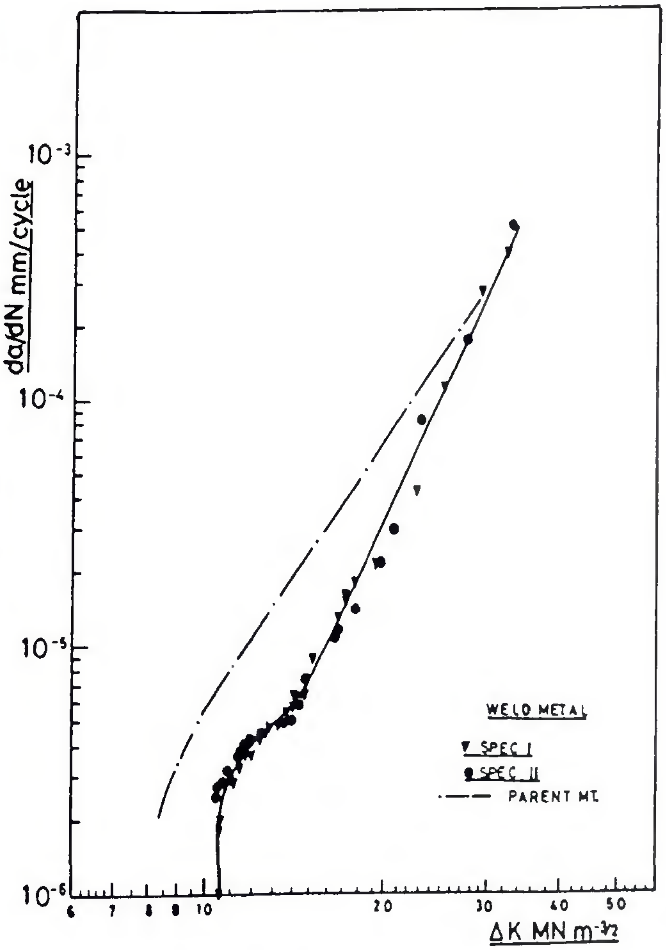

Fig. 5 — Midrange FCG rate data for the WM.

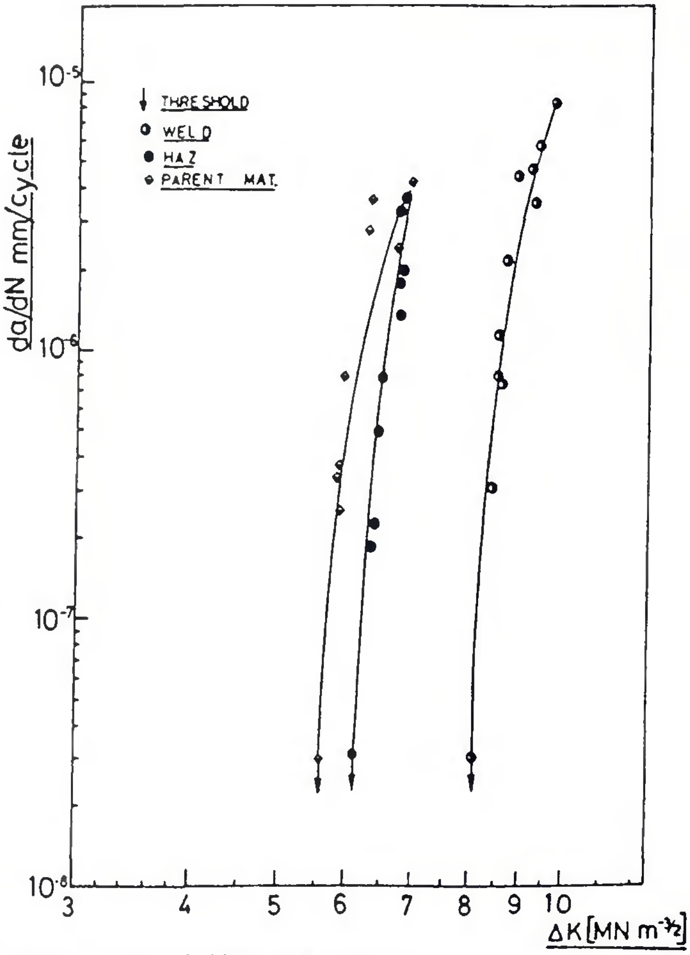

Fig. 6 — Near threshold FCG data (all zones).

ferent from those of the BM. This becomes important in near threshold growth where the FCG rate is very sensitive to the microstructure (Refs. 15, 16). Furthermore, the WM has a much coarser grain structure. A coarse grain structure is more resistant to FCG (Ref. 15), which contributes to the lower rate of FCG near the threshold in this case.

Heat-Affected Zone

The results presented previously indicate a faster rate of FCG in the HAZ than in the BM in the midrange. The graphs cross over as the threshold is approached. This is a clear departure from most reported results, which indicate a lower rate of FCG through the HAZ (Refs. 9–12). This behavior can be attributed to the reasons stated below.

Micromechanisms of FCG

In the midrange of FCG, the growth of fatigue cracks occurs by striation formation (Refs. 17, 18). This material was seen to have an unacceptably high concentration of nitrogen. The heating that occurs in the HAZ due to welding is likely to cause the formation of brittle nitrides in the HAZ. Such an effect was observed by Gardner (Ref. 19). In fatigue, these brittle particles will fail by a "static" mechanism — most likely debonding from the rest of the material. These "static" failure mechanisms, superimposed on the striation formation mechanism, will result in a higher rate of FCG through the HAZ. Near the threshold, the stresses are too low for the "static" modes of failure to take place and, as is evident from Fig. 4, the gap between FCG rates in the HAZ and BM closes.

Hydrogen Embrittlement

As was explained in the introduction, lack of adequate quality control procedures leads to the hot metal coming into contact with water during rolling. Thus, some water vapor/hydrogen is likely to be trapped in the metal. This effect may be further aggravated during welding when hydrogen, both from residual water vapor and from the electrode cover (all the welding was done using the shielded metal arc method) diffuse to the HAZ. The result is hydrogen embrittlement in the HAZ, leading to the higher rate of FCG. Higher rates of FCG caused by hydrogen embrittlement in structural steels has been reported by Marrow, *et al.* (Ref. 20), Cotterill and King (Ref. 21), and Hippsley and Lane (Ref. 22), among others.

Coarser Grains

Similar to what was said for the weld metal, coarser grains in the HAZ lead to a lower rate of FCG in the near threshold regime (Ref. 15).

The most serious anomalous behavior of the material subject to study was the higher rate of FCG through the HAZ. This is attributable to the lack of quality control both during casting/rolling of the steel and during fabrication of the bus body frameworks. It is recommended that both the steel rolling mills and the bus body fabricators institute quality control assurance procedures which should include:

1) proper control of the chemistry of the melt through chemical/spectrophotometric analysis.

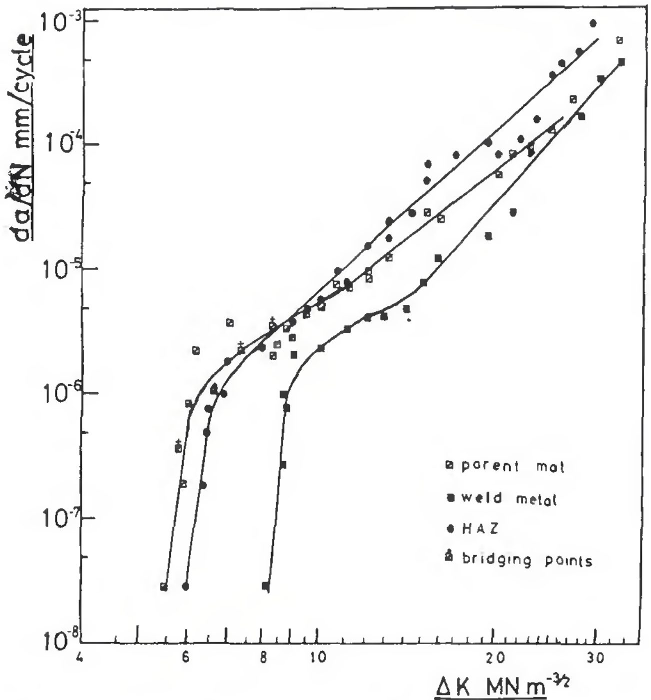

Fig. 7 — Combined regime I and II FCG data (all zones).

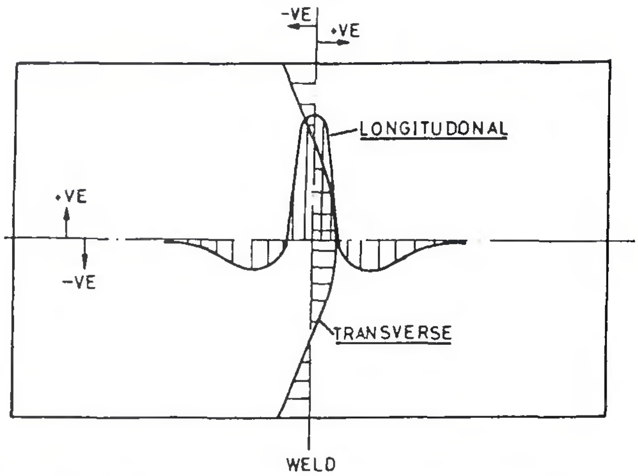

Fig. 8 — Schematic distibution of welding residual stresses.

2) appropriate degassing of the melt.

3) prevention of excessive contact between the hot metal and water during rolling. (The water is used to cool the rollers. The solution could be to either use an alternative method of cooling or to ensure better sealing of the water pipes.)

4) dry the welding electrodes prior to use to exclude water vapor.

5) using electrodes of higher quality to exclude the possibility of hydrogen absorption.

It may also be of interest to quantify the effects of the factors mentioned above, *i.e.*, the residual stresses, crack branching and kinking, as well as the nitride formation tendency. Except for residual stresses, for which several researchers (Refs. 7, 23) have suggested equations, quantifying the other factors is no easy task. A statistical approach may be the only path.

Conclusions

The following conclusions may be drawn from this study of the effects of welding on the rate of FCG in a low-carbon structural steel:

1) In the midrange of FCG, the FCG rate is highest in the HAZ and lowest in the WM.

2) The high FCG rate through the HAZ may be attributed to the formation of nitrides, and hydrogen embrittlement in the HAZ, though other factors may also be contributing.

3) The slower FCG rate through the weld metal was due to residual stresses and weld micro-imperfections, which lead to changes in crack tip morphology.

4) The threshold stress intensity range increased in the order BM < HAZ < WM.

5) The greater resistance of the HAZ and the WM to near threshold FCG was due to the coarser grain structures in these zones, and, in the case of WM, partially to compressive residual stresses.

Acknowledgments

Financial support for this study was provided by the German Academic Exchange Service (DAAD).

References

1. ISO 630, Structural Steels. International Organization for Standardization, (1980).
2. Cartwright, D. J., and Rooke, D. P. *Compendium of Stress Intensity Factors.* HMSO, London, (1976).
3. ASTM E647, Test Method for Constant Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/cycle. *Annual Book of ASTM Standards.* part 10. (1980).
4. Gurney, T. R. *Fatigue of Welded Structures,* Cambridge University Press, (1979).
5. Nakamura, H., *et al. J. Testing and Evaluation,* Vol. 16. No. 3, p. 280, (1988).
6. Yuen, J. L., and Coperland, J. F. ; *J. Eng. Mat. and Tech.,* Vol. 101, p.214, (1979).
7. Itoh, Y. Z. *et al. Eng. Fracture Mech.;* Vol. 33, No. 3, p. 397, (1989).
8. Greasley, A. and Naylor, S. G. W. Eng. *Fracture Mech.,* Vol. 24, No. 5, p.717, (1986).
9. Clark, Jr., W. G. ASME paper No. 70-PVP-24, (1970).
10. Bucci, R. J. Greene, B. N. and Paris, P.C. ASTM STP 536, (1973).
11. Shahinian, P., *et al. Welding Journal.,* Vol. 51, No. 11, (1972).
12. James, L. A. HEDL-TME 76-93,Westinghouse Hardford Co. Rictuand,WA, (1977).
13. James, L. A., and Mills, W. J. J. Eng. Mat. and Tech. Vol. 107, p. 34, (1985).
14. Maddox, S. J. *Welding Journal,* Vol. 53, No. 9, (1974).
15. Ritchie, R. O. Metal Science, (1979).
16. Shih, T. T., and Donald, J. K. J. Eng. *Mat. and Tech.,* Vol. 103, (1981).
17. Pelloux, R. M. N. *Eng. Frac. Mech.* Vol.1, (1970).
18. Laird, C. ASTM STP 415, (1967).
19. Gardner, J. *Welding Engineering Science and Metallurgy.* Norman Price Ltd., (1972).
20. Marrow, T. J. Cotterill, P. J., and King, J. E.; *Acta Metall. Mater.,* Vol. 40, No. 8, pp. 2059-2068, (1992).
21. Cotterill, P. J., and King, J. E.; *Int. J. Fatigue,* Vol. 13, No 6, pp. 447–452, (1991).
22. Hippsley, C.A., and Lane, *C. E. Mat. Sci. Tech.,* Vol. 6, pp. 735-742, (1990).
23. Beghini, M., and Bertini, J. *Eng. Fracture Mech.,* Vol. 36, No. 3, p. 397, (1990).

Appendix

Nomenclature

a	half crack length
C	constant in the Paris equation
da/dN	fatigue crack growth rate
K	stress intensity factor
K_{max}	maximum value of K during cyclic loading

K_{min}	minimum value of K during cyclic loading
ΔK	range of stress intensity
K_c	plane stress fracture toughness
ΔK_{th}	threshold stress intensity range
m	exponent in the Paris equation
N	number of stress cycles
P	load
R	stress ratio K_{min}/K_{max}

Abbreviations

ASTM	American Society for Testing and Materials
CCS	Center Cracked Tension Specimen
FCG(P)	Fatigue Crack Growth (Propagation)
HAZ	Heat-Affected Zone
ISO	International Organization for Standardization
NTFCG	Near Threshold Fatigue Crack Growth
BM	Base Metal
WM	Weld Metal

WRC Bulletin 369
December 1991

Nitrogen in Arc Welding — A Review

By IIW Commission II

In 1983, Commission II of the International Institute of Welding (IIW) initiated an effort to review and examine the role of nitrogen in steel weld metals. The objective was to compile in one source, for future reference, the available information on how nitrogen enters weld metals produced by various arc welding processes, what forms it takes in these welds, and how it affects weld metal properties.

This bulletin contains 13 reports and several hundred references related to Nitrogen in Weld Metals that has been prepared as a review to show the importance nitrogen has in determining weld metal properties.

Publication of this report was sponsored by the Welding Research Council, Inc. The price of WRC Bulletin 369 is $85.00 per copy, plus $5.00 for U.S. and $10.00 for overseas, postage and handling. Orders should be sent with payment to the Welding Research Council, Room 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 370
February 1992

Recommendations Proposed by the PVRC Committee on Review of ASME Nuclear Codes and Standards Approved by the PVRC Steering Committee

The ASME Board on Nuclear Codes and Standards (BNCS) determined in 1986 that an overall technical review of existing ASME nuclear codes and standards was needed. The decision to initiate this study was reinforced by many factors, but most importantly by the need to capture a pool of knowledge and "lessons learned" from the existing generation of technical experts with codes and standards background.

Project responsibility was placed with the Pressure Vessel Research Council and activity initiated in January 1988. The direction was vested in a Steering Committee which had overview of six subcommittees.

The recommendations provided by nuclear utilities and industry were combined with the independent considerations and recommendations of the PVRC Subcommittees and Steering Committees.

Publication of this document was sponsored by the Steering Committee on the Review of ASME Nuclear Codes and Standards of the Pressure Vessel Research Council. The price of WRC Bulletin 370 is $30.00 per copy, plus $5.00 for U.S. and $10.00 for overseas, postage and handling. Orders should be sent with payment to the Welding Research Council, Room 1301, 345 E. 47th St., New York, NY 10017.