WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, MAY, 1983

Sponsored by the American Welding Society and the Welding Research Council

Significance of Blunt Flaws in Pipeline Girth Welds

Crack initiation from porosity, slag and arc strikes is negligible under the essentially static loading to which tough pipeline girth welds are subjected

BY M. B. KASEN

ABSTRACT. The probability of crack initiation from porosity, slag inclusions, and arc strikes in pipeline girth welds was investigated by subjecting highly flawed welds to severe low-cycle, fully-reversed, strain-controlled fatigue. No effect of the flaw type or content was observed on the number of cyclic reversals to fatigue crack initiation when tested with the weld reinforcement intact.

Fracture was, in all cases, dominated by the geometrical discontinuity formed by the reinforcement. As the applied strain levels were well above yield, these results indicated that the probability of crack initiation from such flaws would be negligible under the essentially static loading to which pipelines are normally subjected. This was corroborated by static tensile testing of flawed welds.

Introduction

The National Bureau of Standards recently completed an extensive program aimed at developing techniques for applying fitness-for-purpose criteria to assessing the quality of girth welds in large diameter pipelines. The study extended the approach previously taken in assessing the significance of weld flaws in the Trans-Alaska oil pipeline (Ref. 1). It was based on the use of fracture mechanics principles to establish accept/reject criteria for flaw size, considering the mechanical properties of the welds and the stress state of the line.

It was recognized, however, that different flaw types have different probabilities of initiating brittle fracture. There is little doubt that planar flaws such as partial joint penetration, lack of sidewall fusion, and underbead cracking are dangerous if they exceed a certain size. But a number of authors have suggested that the history of weld failures, as well as the results of laboratory studies, lead to the conclusion that blunt flaws such as porosity, slag inclusions, and arc strikes, have a very low probability of initiating cracks in tough weld metal, rendering them essentially innocuous in many welds (Ref. 2-7).

If this could be demonstrated for pipeline girth welds, considerable cost savings could result from a simplification of the inspection procedures. A part of the program, therefore, investigated the significance of blunt flaws as brittle fracture initiators in girth welds typical of those anticipated for the Alaska Natural Gas Transmission System (ANGTS).

Procedures

The experimental procedures have been described in an interim report (Ref. 8). A series of girth welds containing large contents of porosity, slag, and arc strikes were fabricated in 1016 mm (40 in.) and in 1219 mm (48 in.) diameter API 5LX-65 and API 5LX-70 pipe.

As illustrated in Fig. 1, the flaw content was equal to or in excess of that anticipated under the worst of field conditions. The arc strikes were made on completed welds so as to retain the hard martensitic structure in the arc strike region. Fully automatic and manual (SMA) processes were represented, with fixturing, consumables, and personnel reflecting field procedures as much as possible. Typical electrode compositions as provided by the fabricator are given in Table 1. Measured weld metal properties are summarized in Table 2.

Except for porosity, flaws were produced by grossly exaggerating the conditions normally causing such flaws. Several unsuccessful attempts were made to naturally produce the desired 12 to 15% radiographic obscuration by porosity during manual welding. Excessive drying of the cellulosic electrodes, breaking the flux cover and improper welding technique produced porosity. However, porosity occurred only in the top of the weld pass, where it was largely removed by the successive pass. Porosity was, therefore, simulated by drilling a pattern of 3.175 mm (0.125 in.) diameter holes in

Table 1—Typical Welding Electrode Compositions, Wt-%[a]

Element	Welding process: Shielded metal arc[b]	Welding process: Automatic[c]
Mn	0.47-0.51	1.35
Si	0.07-0.10	0.70
Cr	0.12-0.13	–
Ni	1.03-1.70	1.15
Mo	0.01	–
V	0.02-0.03	–
C	–	0.10
S	–	0.015
P	–	0.015

(a) Reported by the fabricator.
(b) AWS E8010G.
(c) AWS E70S-6.

Paper presented at the 64th AWS Annual Convention held in Philadelphia, Pennsylvania, during April 25-29, 1983.

M. B. KASEN is with the Fracture and Deformation Division, National Bureau of Standards, Boulder, Colorado.

five successive interior passes and welding over them. This produced the result illustrated in Fig. 1C.

Large, transverse weld specimens, each 736 mm (29 in.) long and containing 101.6 mm (4 in.) of weld across the reduced section, were prepared from the welded pipes. The specimens were subjected to fully-reversed, strain-controlled, low-cycle fatigue, producing a stress-strain hysteresis loop as illustrated in Fig. 2. The imposed strain was either just over weld metal yield (±0.22%) or approximately twice yield (±0.45%).

The desired strain range was initially established by strain gages located at the weld, while the 4.45 MN (1×10^6 pound-force) servohydraulic test machine was controlled by an extensometer spanning the weld region. A temperature of -2 ± 1°C (28.4 ± 1.8°F) was maintained to simulate the lowest anticipated service temperature of the ANGTS line. As cyclic loading proceeded, cracks developing in the weld region reduced the effective cross-sectional area, causing a drop in the load required to maintain the selected strain range. Monitoring of the load, therefore, provided an indication of the number of cyclic reversals required to initiate cracking.

A 10% drop, corresponding to development of about a 10% cracked area, was taken as the criterion for crack initiation. The reason for this was that, once initiated, crack growth rates were quite rapid under the severe test conditions. Cyclic straining was continued until a load drop corresponding to a 40% cracked area was obtained. This facilitated a study of the influence of flaw type on crack propagation. Specimens were then broken in tension.

Pipelines are not subjected to such severe cyclic loading. Nonetheless, this experimental approach was selected, because any flaw found innocuous as a crack initiator under the imposed conditions can conservatively be considered innocuous in essentially statically loaded structures such as a pipeline (Ref. 9). A similar approach has been used to demonstrate the inherently innocuous character of blunt flaws in pressure vessel weldments (Ref. 10,11).

Specimen asymmetry due to maintaining the pipe curvature tended to cause failure in a buckling mode rather than in the tension-compression mode as required for the experiment. We compensated for this by developing the specimen support system illustrated in Fig. 3. To our knowledge, this is the first successful low-cycle fatigue experiment utilizing such a specimen.

Weldments were tested in fatigue with the face reinforcement both intact and removed. The former were of most direct interest in assessing flaw significance, as they duplicated the field condition. But testing with the reinforcement removed to force failure through the flawed regions of the welds was useful in studying flaw interaction during initiation and propagation of cracks.

Several sound automatic welds, automatic welds containing porosity, and manual welds containing simulated porosity were also pulled to failure in tension at -2 ± 1°C, (28.4 ± 1.8°F), with the reinforcement intact. The purpose was to validate the assumption that the flaws shown to be innocuous during fatigue loading were also innocuous under static loading.

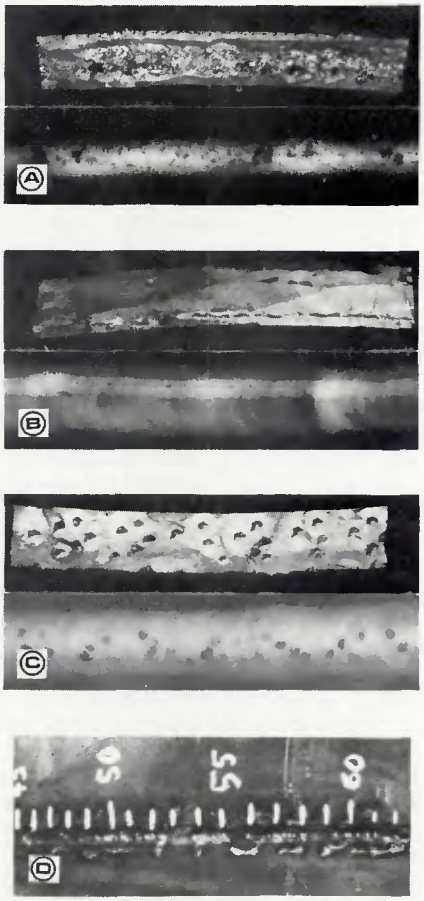

Fig. 1—Typical levels of weld flaws studied in the experiment; porosity in the manual (SMA) weld was simulated by drilling 3.175 mm (0.125 in.) diameter holes in five successive interior weld passes and overwelding: A—automatic porosity, 15% obscuration; B—slag from manual welding; C—simulated porosity, 13% obscuration; D—arc strikes. Upper views in A, B, C and D—fracture appearance; lower views—radiographic appearance

Table 2—Typical Weld Metal Properties

Weld type	Hardness	Yield strength at 0.2% offset, 25°C psi × 10^3	(MPa)	Toughness (0°C COD)[a], mm
Automatic	HRC 30	725.0	(105.5)	0.084
Manual	HRB 91	465.0	(67.5)	0.226

(a) COD—crack opening displacement.

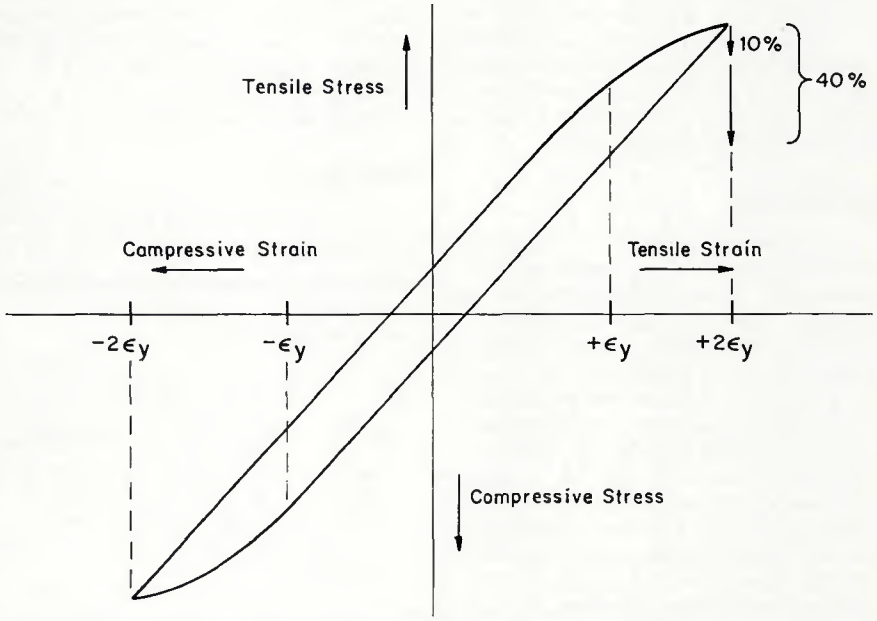

Fig. 2—Schematic of test program. Specimens were placed in alternating tension and compression, with strain controlled at approximately twice weldment yield ($2\epsilon_y = 0.45\%$) or slightly over weldment yield ($\epsilon_y = 0.22\%$). Hysteresis loops were observed at both strain levels. Crack initiation defined as a 10% drop in load required to maintain the desired strain range. Specimens were broken in tension after a 40% load drop

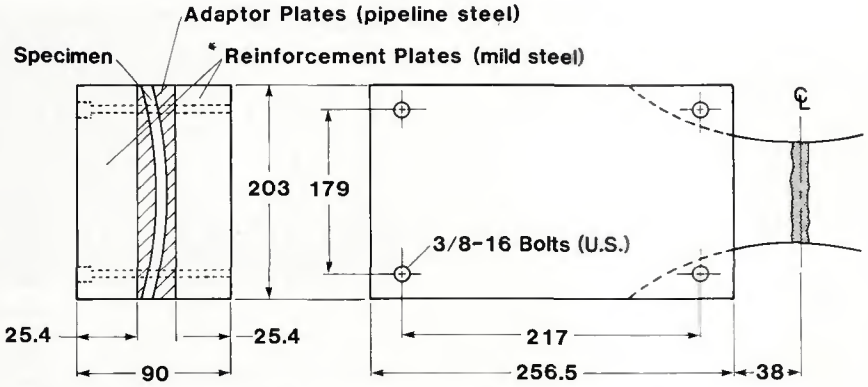

Fig. 3—Specimen support system for low-cycle fatigue. Dimensions in mm

Results

The results of tests performed with the weld reinforcement intact are summarized in Fig. 4. Here, the number of cyclic reversals required to initiate cracking is plotted as a function of the strain range to which each weld was subjected. Data from flawed welds, sound welds, and unwelded pipe material are included. The effects of individual flaw types are illustrated in Fig. 4A, 4B, and 4C, while all test results are combined in Fig. 4D.

The data show that some welds containing porosity or slag initiated cracking at fewer cycles than did sound welds—others at a greater number of cycles. A minimum of 30 reversals at twice yield or about 450 reversals at just over yield were required, regardless of porosity, slag, or arc strikes. The much better performance of the unwelded plate specimens (compared to any of the welded specimens) suggests that weld cracking is dominated by the stress and strain concentration at the edge of the weld reinforcement contour, regardless of flaw content.

All weld failures initiated at this location, with propagation predominantly following the fusion line. The fracture passed through slag lying close to the fusion line, and occasionally through some porosity; however, neither crack initiation nor propagation was affected by the presence of the arc strikes adjacent to the weld reinforcement. It was necessary to place arc strikes at the reduced section of base metal specimens and to cyclically strain at twice the yield strength before their influence was detected. Even here, 900 cycles were required for a crack to initiate from an arc strike.

It has frequently been observed that low cycle fatigue life, N, can be expressed as a function of total strain range, $\Delta\epsilon_t$, by a relationship of the form

$$\Delta\epsilon_t N^m = \text{constant} \qquad (1)$$

implying a straight line relationship between log $\Delta\epsilon_t$ and log N, having a slope of −m. Gurney (Ref. 9) has noted that results reported by a number of investigators for steel weldments of different configurations fall within a relatively nar-

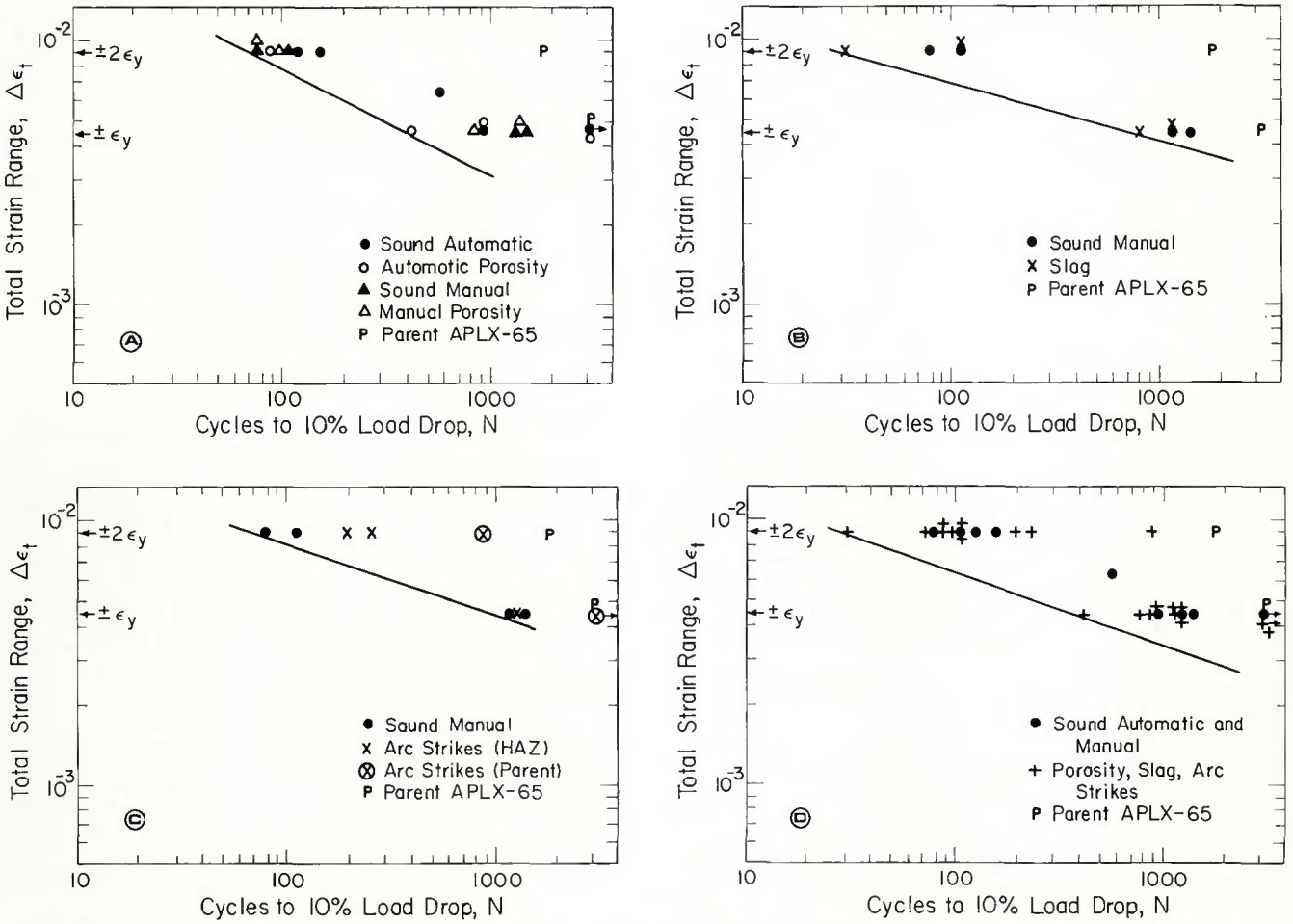

Fig. 4—Cyclic reversals required to initiate fatigue cracking (10% load drop) as a function of strain range for base metal, sound welds, and welds containing blunt flaws. Results are combined in (d). All welds tested at −2 ± 1°C (28.4 ± 1.8°F) with reinforcement intact

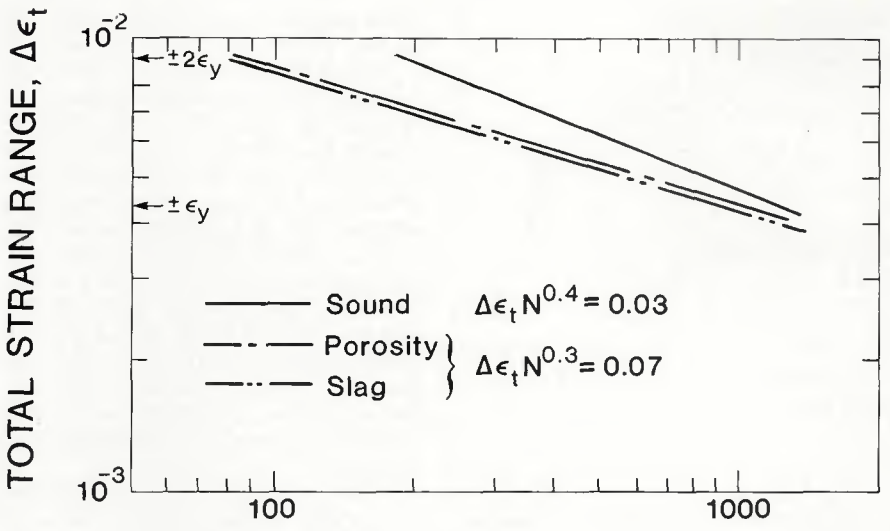

Fig. 5 – Averages of lifetime to crack initiation following equation (1) for specimens with weld reinforcement intact

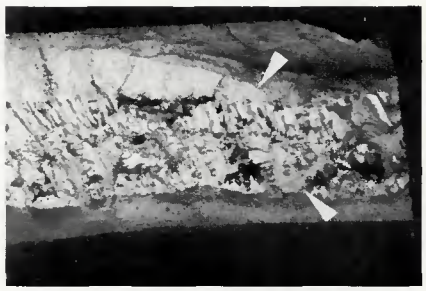

Fig. 6 – Crack propagation in an automatic weld containing porosity, tested at ±0.22% strain, with weld reinforcement removed. Arrows define single crack front propagating from left to right through the porous region without evidence of initiation from individual pores ahead of the advancing front. Thickness through weld is approximately 15 mm (0.6 in.)

row scatter band on such a plot, producing a slope of approximately $-\frac{1}{3}$.

Figure 5 illustrates that a very similar result is obtained when the average number of cycles to crack initiation is plotted as a function of total strain range for manual welds tested with the reinforcement intact in the present program. Welds containing porosity and slag produced a relationship of the form $\Delta\epsilon_t N^{0.3} = 0.03$. However, the averaged data from welds free of internal flaws, but including those containing arc strikes, appeared to form a different population following the relationship $\Delta\epsilon_t N^{0.4} = 0.07$. This is reflected in the divergence observed between the sound and flawed weld data for the higher ($\pm 2\epsilon_y$) strain range on Fig. 5; it suggests that the high porosity and slag content of the welds may have somewhat reduced the cyclic life to crack initiation under this most severe test condition. On the other hand, coincidence of the data plots at the lower ($\pm \epsilon_y$) strain range suggests that the flaws had no effect on cyclic life under this test condition.

Weldments tested with the reinforcement removed to force failure through the flawed regions initiated cracking at fewer reversals than was required for weldments tested with the reinforcement intact. But, even under this abnormally severe test condition, 26 cycles were required for initiation at $\pm 2\epsilon_y$, and 132 cycles were required at $\pm \epsilon_y$.

Fractographic examination of these welds containing porosity and slag showed a negligible interaction between the flaws in initiation or propagation of the cracks at the lower strain level. Despite the very high level of automatic porosity, Fig. 6 illustrates that cracks propagated as a single front through the flawed region, with little evidence of cracking from pores ahead of the front. At the higher strain level, initiation and coalescence of cracks from individual pores was observed.

Specimens welded by the shielded metal arc process revealed the presence

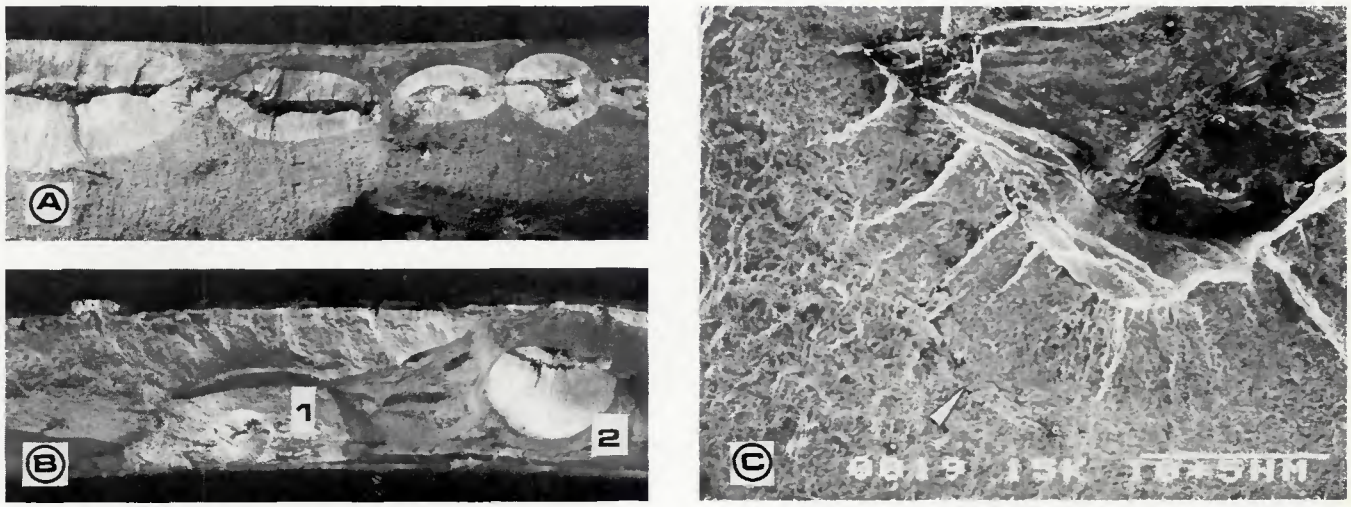

Fig. 7 – Fisheye cracks originating at: A – slag inclusions; and B – at micropores in manual (SMA) welds; arrow in C defines boundary between brittle fracture within a fisheye formed at a slag inclusion and ductile fracture outside the fisheye. In B, a small fisheye penetrating the surface at location 1 served as a fatigue initiation point, whereas the much larger buried fisheye at location 2 did not do so

Table 3—Ultimate Tensile Strength for Welds Pulled to Failure in Tension at −2°C (± 1°C) (28.4° ± 1.8°F)[a]

Condition	Ultimate tensile strength, psi × 10^3	(MPa)	Radiographic obscuration, %
Sound welds—automatic welding	651	(94.4)	None
	648	(94.0)	
Automatic welding porosity	665	(96.4)	~15
	651	(94.4)	
Manual welding porosity	675	(98.0)	~12
	681	98.8)	

(a) Weld reinforcement intact; all base metal or fusion line failures.

of halos surrounding slag and porosity flaws on the fracture surface. This phenomenon, illustrated in Fig. 7, was observed in radiographically sound as well as in flawed welds, at both strain levels, and in specimens tested with the weld reinforcement intact and removed. The literature describes these features as "fisheyes" because the halo is often centered on a micropore (Refs. 12,13).

The formation of fisheyes is not well understood. However, their presence is believed to reflect hydrogen embrittlement of the region adjacent to pores and surfaces to which hydrogen has segregated during the welding operation. A lack of fatigue striations within the fisheye region supports this interpretation. Fisheyes are known to develop under static stress (Ref. 12) as well as under dynamic stress (Ref. 13). They have only been reported in metal strained beyond yield, suggesting that they reflect a stress-induced diffusion of hydrogen from the segregated site into the surrounding weld metal. If this interpretation is correct, it must be concluded that hydrogen segregated in this manner is very stable, because the welds were tested 1½ years after fabrication.

Fisheyes are sharp cracks lying normal to the direction of applied stress. Thus, it might be assumed that fisheyes would play a major role in initiation and propagation of fatigue cracks. But this did not appear to be the case in the present study, except where the fisheye penetrated the specimen surface. As an example, the primary fatigue crack in the specimen illustrated in Fig. 7B initiated and propagated from a small fisheye near the surface, rather than from the very large fisheye in the interior of the weld.

Several sound automatic welds, and automatic and manual welds containing porosity, were also tested in static tension at a temperature of −2 ± 1°C (28.4 ± 1.8°F) with results given in Table 3. No effect of the flaw content was observed in the fracture strength. All specimens failed at the fusion line or in the base material.

Discussion and Conclusions

This study has shown that the probability of crack initiation from porosity, slag, and arc strikes during low-cycle fatigue was very low in the manual and automatic pipeline girth welds tested in this program. Some indication of a reduction in cyclic life to crack initiation was noted when welds containing large quantities of porosity and slag were cycled at the highest strain range. Nonetheless, the geometrical discontinuity formed by the weld reinforcement was found to dominate the fatigue failure mode in all tests conducted with the reinforcement intact.

Even with the reinforcement removed to force failure through the highly flawed weld metal, the welds showed a high tolerance to fatigue crack initiation from the blunt flaws. Because strain levels were well above yield, the data indicate that the probability of crack initiation from such flaws would be negligible if such welds were subjected to the essentially static loading conditions of operating pipelines.

Results suggest that porosity, slag inclusions, and arc strikes may be innocuous as fracture initiation sites in girth welds fabricated with materials currently used in pipeline construction. It must be noted, however, that this conclusion is valid only for weld metals providing toughness equal to or higher than that studied in the present program, and only for the temperature investigated. It is not necessarily valid for weld metal toughnesses less than those given in Table 2, or for lower temperatures, where toughness decreases. Under such conditions, it is recommended that blunt flaws be considered as sharp flaws of equal dimensions and that their significance be assessed by reference to appropriate allowable flaw size curves constructed on fracture mechanics principles for the prevailing conditions (Ref. 1).

This procedure is greatly simplified by the results of a separate study (Ref. 14) that has shown the maximum through-wall dimensions of slag and porosity to be limited to the depth of an average weld pass in a multipass girth weld. The relationship between the width of an arc strike and its depth has already been established (Ref. 1). Through-wall dimensioning of such flaws is, therefore, not required for such an analysis.

These results are not to be interpreted as evidence that existing quality control standards limiting the allowable quantity of blunt flaws should be drastically liberalized. Although the present data suggest that such flaws may be ignored from the point-of-view of brittle fracture, excessive flaw content is indicative of incorrect welding practice, of serious problems with welding equipment or consumables, or of other problems that could introduce serious undetectable flaws into the weldment. For example, Harrison (Ref. 3) has noted that aligned porosity is frequently associated with undetected, partial joint penetration.

There are also good technical reasons for limiting the content of porosity to a level that will not interfere with the detectability of damaging planar flaws. Nondestructive testing has two roles to play. One relates to quality control, the other to acceptance or rejection of a weld on the basis of fitness-for-purpose. Only the latter is addressed in this paper.

Acknowledgments

This work was supported by the Office of Pipeline Safety Operations, U.S. Department of Transportation, L. Ulrich, contract monitor. The girth welds were fabricated by the H. C. Price Company, Dewey, Oklahoma, under the supervision of R. Gwin and S. Madden. The manual welds containing artificially-introduced porosity were prepared by The Lincoln Electric Company, Cleveland, Ohio, under the direction of J. E. Hinkel. The low-cycle fatigue studies were conducted at the Denver facility of the Martin-Marietta Corporation, by J. Shepic and R. Gibb. Radiographic support was provided by the Rocky Flats Division, Rockwell International Corp., Golden, Colorado, under the direction of J. Summers.

The author wishes to thank all of these companies and individuals for their support. The assistance of Dr. R. Mikesell and of many other individuals at NBS is also gratefully acknowledged.

References

1. Reed, R. P., McHenry, H. I., and Kasen, M. B. 1979 (January). *A fracture mechanics evaluation of flaws in pipeline girth welds,* Welding Research Council Bulletin 245.

2. Harrison, J. D. 1971. Low cycle fatigue tests on welded joints in high strength steels. *Proceedings, conference on fatigue of welded structures,* U.K., The Welding Institute:194-207.

3. Harrison, J. D. 1972. The basis for a proposed acceptance standard for weld

defects, part 1: porosity, *Metal Construction and British Welding Journal* 4(3):99-107 (cf. *I.I.W. document XIII-624-71*).

4. Harrison, J. D. 1972. The basis for a proposed acceptance standard for weld defects, Part 2: slag, *Metal Construction and British Welding Journal* 4(7):262-268 (cf. *I.I.W. document VF-62-72 OE*).

5. Burdekin, F. M. *Effect of porosity, slag inclusions and surface profile on brittle fracture in ferritic steel weldments.* I.I.W. document X-642-71.

6. Kihara, H., Ishii, Y., Koshiga, F., and Fuji, T. *Brittle fracture behavior of welded joints including various types of welding defects.* I.I.W. document X-557-70 (VF-47-70 OE).

7. Ishii, Y., and Iida, K. 1972. An analysis of intermediate cycle fatigue strength of defective weld joints. *Transactions of the Japan Welding Society* 3(2):1-8.

8. Kasen, M. B., and Mikesell, R. P. 1980. Interim report on the significance of blunt flaws in pipeline girth welds. *Pipeline and energy plant piping:* 329-336. Toronto, Canada: Pergamon Press. (cf. *Oil and Gas Journal*:1981 (March 30):155-158).

9. Gurney, T. R. 1979. *Fatigue of welded structures,* 2nd ed. United Kingdom: Cambridge University Press.

10. Boulton, C. F. 1977. Acceptance levels of weld defects for fatigue service. *Welding Journal* 56(1):13-s to 22-s.

11. Harrison, J. D., Archer, G. L., and Boulton, C. F. 1978. Significance of defects in pressure vessels under fatigue loading. *Tolerance of flaws in pressurized components:* 255-270. London: The Institution of Mechanical Engineers.

12. Bailey, N. 1974. *Fisheyes, hydrogen embrittlement, and removal.* Welding Institute research bulletin, vol. 15: 369-371.

13. Matting, A., and Neitzel, M. 1967. The influence of weld defects on the fatigue behavior of welded constructions. *British Welding Journal* 14(1):3-12.

14. Kasen, M. B., and Hicho, G. E., Inherent limitations in through-wall depths of blunt flaws in pipeline girth welds. In preparation. Boulder, Colorado: National Bureau of Standards.

WRC Bulletin 281
October, 1982

Hydrodynamic Response of Fluid Coupled Cylinders, Simplified Damping and Inertia Coefficients
by S. J. Brown

This study presents the development of the concept of inertia and damping coefficients in an historical context with experimental, classical and numerical investigations into the dynamics of fluid coupled cylinders. It is shown that coefficients may be used to account for coaxial cylinder end conditions, eccentricity, skewness, clusters, shell modes and axial modes.

Publication of this report was sponsored by the Subcommittee on Dynamic Analysis of Pressure Components of the Pressure Vessel Research Committee of the Welding Research Council.

The price of WRC Bulletin 281 is $11.50 per copy, plus $3.00 for postage and handling (foreign + $5.00). Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Room 1301, New York, NY 10017.

WRC Bulletin 282
November, 1982

Elastic-Plastic Buckling of Axially Compressed Ring Stiffened Cylinders—Test vs. Theory
by D. Bushnell

Concern for the safety of nuclear plants and offshore structures has stimulated efforts to determine buckling characteristics of stiffened cylindrical steel shells.

In this paper, BOSOR 5 computer programs were used to predict buckling loads of forty axially compressed mild steel cylindrical shells previously tested at Chicago Bridge & Iron Co.

Publication of this report was sponsored by the Subcommittee on Shells of the Pressure Vessel Research Committee of the Welding Research Council.

The price of WRC Bulletin 282 is $10.75 per copy plus $3.00 for postage and handling (foreign + $5.00). Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Room 1301, New York, NY 10017.