Modified Implant Test for Studying Delayed Cracking

The implant test was modified with a helical notch and used to test HY-80 and HY-130 plate and E10018 and E14018 weld metal for susceptibility to delayed cracking

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ABSTRACT. Previous studies of hydrogen cracking in HY-130 have been conducted with tests that have produced conflicting results. However, an implant test has been developed that eliminates some of the problems associated with other cracking tests.

The implant test was modified in this investigation to improve the reproducibility of the notch location with respect to the weld-metal interface. Subsequently, the cracking tendencies of both weld and base metals in the HY-80 and HY-130 systems were evaluated with the modified implant test.

Implant tests revealed that the particular heat of HY-130 steel tested had a susceptibility to cracking that was similar to an HY-80 steel known to be highly crack sensitive. However, as a result of the lower permissible moisture content of the electrodes and the closer match of the weld metal and base metal strength in an HY-130 weldment, the heat-affected zone experiences both lower hydrogen content and less severe restraint than in an HY-80 weldment. As a consequence, it is likely that there is less tendency for delayed cracking in the heat-affected zone of production welds in HY-130 than in HY-80 steel of comparable crack susceptibility.

The E14018 weld metal showed slightly less cracking susceptibility than HY-130 in the implant test. However, since the hydrogen content and restraint level are generally higher in the weld fusion zone than in the base plate, delayed cracking is more likely to be associated with the weld zone than the heat-affected zone in an HY-130 weldment joined with E14018 electrodes.

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Introduction

Quenched and tempered low-alloy steels such as HY-80 have been used in the as-welded condition at the 80 ksi yield strength level since the late 1950's. In the mid 1960's, a base metal/filler metal system was developed to be used at the 130 ksi yield strength level in the as-welded condition (Refs. 1,2). Both alloys are subject to hydrogen-assisted cracking* and the maximum permissible moisture content of electrodes has been reduced from the 0.2% specified for HY-80 to 0.1% for welding HY-130 (Ref. 1).

Delayed cracking in HY-80 has been associated predominantly with the base metal heat-affected zone, the partially melted zone, and the unmixed zone near the weld interface (Ref. 3). The cracks normally propagate parallel to the fusion line indicating they are caused by stresses oriented transverse to the weld.

On the other hand, HY-130 weldments are reported to be more likely to exhibit cracking in the weld metal than in the base metal (Refs. 2,4,5). These cracks are generally oriented perpendicular to the welding direction, indicating that longitudinal stresses are responsible.

* *The term "hydrogen-assisted cracking" is intended to apply to all forms of cold cracking, including underbead cracking, toe cracking, delayed cracking, etc.*

Since steels generally exhibit an increase in susceptibility to delayed cracking with an increase in hardness (Ref. 6), one would expect HY-130 to be more susceptible than HY-80. However, HY-130 is reported to be less susceptible to delayed cracking than HY-80 (Refs. 7,8). In this regard, it is significant that HY-80 is normally welded with an overmatching electrode (E10018) while the filler metal used with HY-130 (E14018) has approximately the same yield strength as the base metal. Thus, the combination of residual and service stresses tends to cause the HY-130 weldment to deform as a unit, while in an HY-80 weldment, the weaker base metal experiences more plastic deformation than the weld metal, which behaves elastically up to a higher stress level. This situation may help to explain the apparent anomaly in the susceptibility of HY-130 to delayed cracking.

Conditions Necessary for Hydrogen-Assisted Cracking

Although there is considerable controversy over the mechanism of hydrogen-induced cracking, it is generally agreed that there are four requisites for hydrogen-assisted cracking:

1. A critical concentration of hydrogen at the crack tip
2. Stress intensity of sufficient magnitude
3. A susceptible microstructure
4. Temperature in the range of −150 to 400 F (−100 to 200 C).

Hydrogen is postulated to exist in both diffusible (atomic) and non-diffusible (molecular) forms in a steel

(Ref. 9). The molecular hydrogen (H_2) is believed to collect in voids and to develop extremely high hydrostatic pressures under some circumstances (Ref. 10).

Diffusible hydrogen is believed to consist of atomic hydrogen (H) at dislocations, grain boundaries, vacancies, and in the tetrahedral voids in both face-centered-cubic and body-centered-cubic structures (Ref. 9). By interaction with dislocations, diffusible hydrogen is postulated to migrate to regions of high triaxial stress and cause the reversible type of embrittlement exhibited by high-strength steels (Ref. 11).

Residual stresses of approximately yield-strength magnitude are always present in arc welds and often exhibits a high degree of triaxiality (Ref. 12). The superposition of service stresses, therefore, tends to cause localized plastic flow in both the weld metal and the heat-affected zone.

With regard to the influence of microstructure, lower temperature transformation products such as martensite and lower bainite are generally more susceptible to hydrogen-assisted cracking than are elevated temperature transformation products such as upper bainite and pearlite.

Notched tensile tests indicate a pronounced decrease in notch tensile strength of hydrogen charged steels at testing temperatures between −150 and 400 F (−100 and 200 C) (Ref. 13). However, the notch tensile strength appears to be unaffected by the presence of hydrogen at testing temperatures both above and below this range. Unfortunately, the maximum decrease in notch tensile strength tends to occur in the vicinity of ambient atmospheric temperatures (Ref. 13).

Tests for Evaluating Susceptibility to Hydrogen-Assisted Cracking

Both direct and indirect tests have been used to study the susceptibility of steels to hydrogen-assisted cracking. The direct tests involve the deposition of actual welds, usually in some form of specimen designed to provide reproducible conditions of severe restraint. The CTS test, the Y-notch test, and the Lehigh restraint test are three widely used direct tests that are useful for rapid evaluation of relative cracking susceptibility. In all three cases, the rating is made on the basis of the amount of cracking revealed by subsequent metallographic examination. The amount of hydrogen introduced in direct tests is controlled by adjusting the moisture content of flux covered electrodes in SMA welds or, in GMA welds, by additions of hydrogen and/or moisture to the shielding gas.

Direct tests have the advantage of testing the full range of both fusion zone and heat-affected zone microstructures. However, since the restraint level depends upon the geometries of both the specimen and the weld bead, it is difficult to separate effects resulting from the influence of welding procedure on microstructure from its influence on the effective restraint level.

Indirect tests usually involve constant load stress-rupture tests using notched tensile specimens charged with hydrogen either by heat treating in a hydrogen-containing atmosphere or by electrolytic means (Ref. 14). Such tests have the advantage of allowing independent control of stress level, microstructure, and hydrogen content. However, the specimens usually simulate the microstructure found at only one point in the weld heat-affected zone. Furthermore, there is some doubt whether hydrogen introduced by these means either diffuses or is distributed in the same manner as hydrogen introduced via a molten weld pool (Ref. 15).

The cracking susceptibility is rated by conducting a series of constant load rupture tests at various loads until some stress level is reached below which failure does not occur within an arbitrarily specified time. This stress level is defined as the lower critical stress, and is taken as an index of the ability of the material to resist hydrogen-assisted cracking. In addition, an "Embrittlement Index," I, is often calculated from the relationship

$$I = \frac{NTS - LCS}{NTS}$$

where

NTS = short-time notch tensile strength, and

LCS = lower critical stress.

Note that as the susceptibility to hydrogen-assisted cracking increases, the Embrittlement Index also increases.

The Implant Test

Granjon (Refs. 16,17) recently developed a test, called the implant test, that combines certain features of both direct and indirect types of tests.

A small cylindrical test specimen containing a circumferential notch near one end is pressed into a hole drilled in a base metal "specimen plate." A test weld is then deposited on the top surface of the specimen plate to (1) fuse the top end of the test specimen, (2) introduce a controlled amount of hydrogen, and (3) create a weld heat-affected zone that now contains the circumferential notch, as indicated schematically in Fig. 1. The specimen is then loaded in tension and the time to failure noted for a series of tests performed at various stress levels.

The implant test has the following distinct advantages:

1. The stress imposed is independent of the welding procedure used.
2. The effect of welding procedure on microstructure can be investigated independently.
3. The amount of hydrogen introduced can be controlled by adjusting the moisture content of the electrode or the moisture content of the shielding gas in the case of GMA welds.
4. The test specimens are small and simple to machine.
5. The test weld and the specimen plate can be of a composition different from that of the test specimen, since they do not actively participate in the test.

The major difficulty with the test lies in locating the notch properly so that it falls within the same heat-affected zone microstructure in each member of a series of tests. To overcome this problem, a modified implant test, which uses a helical notch in place of the single circumferential notch, was adopted for the current investigation. With this modified specimen, the entire heat-affected zone is traversed by the helical notch and failure initiates and propagates in the most crack-susceptible microstructure. One potential problem involves the fact that the notch is modified at the weld interface during solidification of the weld metal to form an extremely small effective notch radius at the fusion boundary. However, this sharp notch is always located at the interface between the weld fusion zone and the base material. Undercut and incomplete fusion defects in production welds are also located at the weld interface; therefore, it is not considered to be a serious limitation.

Materials and Procedure

Table 1 summarizes the chemical composition of both the base metals and the filler metals used in this investigation. Implant tests were performed on HY-80 and HY-130 base metal specimens and on test specimens machined from all-weld-metal pads deposited both with E10018 and E14018 covered electrodes.

The mechanical properties of the

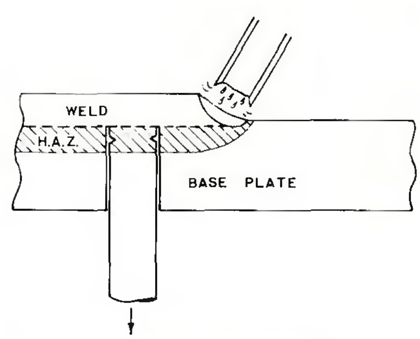

Fig. 1 — Original implant test

Table 1 — Chemical Composition of the Materials Used in this Investigation

Material	Condition	Element, %									
		C	Mn	P	S	Si	Ni	Cr	Mo	V	Ti
HY-80 (Heat P)	2 in. plate	0.18	0.32	0.018	0.013	0.20	2.99	1.68	0.41	—	—
HY-130	2 in. plate	0.11	0.88	0.003	0.003	0.35	4.95	0.53	0.50	0.08	—
E10018	3/16 in. covered electrodes	0.11	1.54	0.010 [a]	0.015 [a]	0.45 [a]	1.44	—	0.36	—	—
E14018	3/16-in. covered electrodes	0.066	0.96	0.004	0.004	0.37	3.53	0.46	0.78	0.01	—
AX-140	1/16-in. bare electrode	0.10	1.86	0.005	0.005	0.43	2.05	0.87	0.54	—	0.01

(a) Typical values of these weld deposits, given by the manufacturer.

materials studied, together with those reported for the AX-140 bare wire electrode used to produce the GMA test weld bead, are contained in Table 2.

Table 3 summarizes the welding conditions used to prepare the two weld pads as well as those used to deposit the GMA test welds.

The weld pads each consisted of four layers of weld metal deposited on a 2 × 8 × 1½ in. thick plate of the HY-80 steel. The resulting weld metal pad was ½ in. thick and covered the entire 2 by 8 in. surface. Figure 2 shows the apparatus used to deposit these weld pads. Travel was provided by a commercially available motor-driven carriage upon which the stick feeder was mounted. Covered electrodes were fed by a feed screw actuated by a motor connected in parallel with the arc. Thus, an increase in voltage caused an increase in feed rate, and the system was adjusted so as to maintain the desired arc voltage automatically.

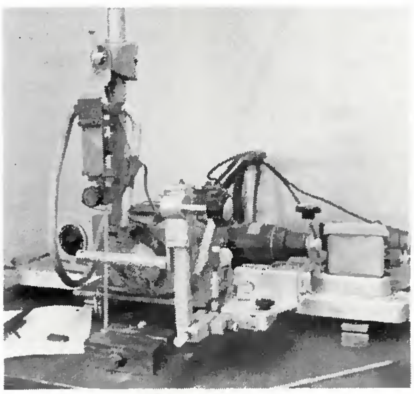

Fig. 2 — Automatic welding unit for shielded metal-arc deposits showing an implant specimen at the left and the hydrogen determination testpiece assembly directly under the electrode

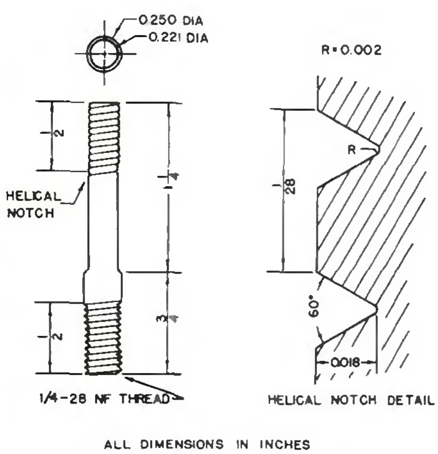

Fig. 3 — Implant specimen details

Specimen Preparation

Figure 3 shows the details of the modified implant specimens. Starting with a ¼ in. diam blank, the end to be notched was machined to a diameter of 0.221 in. for a distance of 1¼ in. The helical notch was then machined in a lathe, as indicated in Fig. 3, using a properly contoured single-point cutting tool. The ¼-28 NF thread on the opposite end was also cut in the lathe in order to insure that the axes of the helical notch, the cylindrical specimen, and the loading threads were coincident.

Implant specimens from both HY-80 and HY-130 were machined with their axes parallel to the short transverse direction of the 2 in. thick plate. An additional series of HY-130 specimens were machined with their axes located approximately at the ¼ thickness plane and oriented parallel to the principal rolling direction.

The all-weld-metal implant specimens were machined with their axes parallel to the short transverse direction of the completed weld pad, with the helical notch located at the end composed of the ½ in. thick weld deposit.

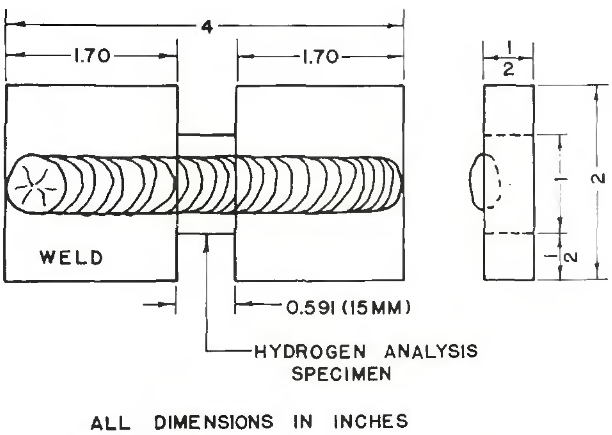

Fig. 4 — Modified hydrogen determination assembly

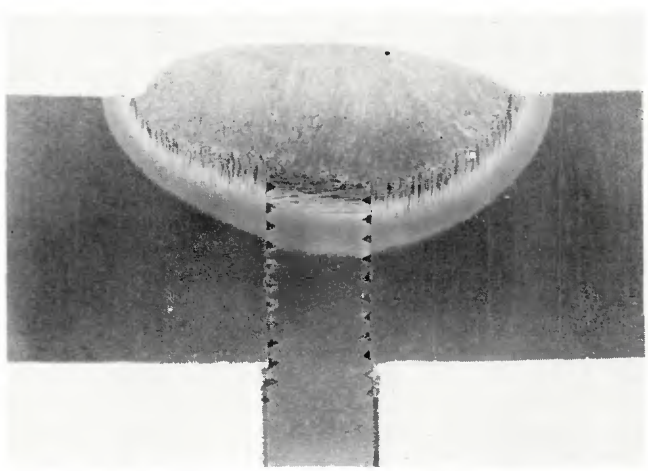

Fig. 5 — Modified implant specimen sectioned near the implant axis. Nital Etch, X3.5, reduced 20%

Implant Test Weld Procedure

The implant test weld was deposited with AX-140 wire by the GMA process, using the conditions summarized in Table 3. The argon shielding gas was bubbled through a 9-in. column of water maintained at room temperature. This caused sufficient moisture pickup to provide a diffusible hydrogen content of 9 cc of hydrogen per 100 g of deposited weld metal, when measured by a standard IIW technique (Ref. 18) immediately after welding. Analyses performed with the same apparatus on a modified specimen subjected to the same procedures and standardized delay times used with the implant test specimens indicated that the hydrogen content at the beginning of the loading operation was actually 6.5 cc/100 g. Figure 4 shows the dimensions and details of the modified specimen used in obtaining this information. Figure 5 shows a transverse section of a typical test weld taken through the axis of the implant specimen. The fact that the fusion boundary and the outer edge of the heat-affected zone are continuous across the interface between the specimen plate and the test specimen indicates that the thermal cycles at a given distance from the fusion boundary must have been the same in both the implant specimen and the specimen plate.

Testing Procedure

Figure 6 shows, in schematic form, the details of the implant machine. The specimen plate is positioned on a supporting plate with the test specimen protruding downward through a hole. The threaded end is inserted in the threaded grip at the top of the loading quill. The loading quill is attached to a pneumatic loading cylinder by a ball-and-socket joint to assure uniaxial loading. A strain gage bridge mounted on the loading quill permits continuous monitoring of the load on the test specimen.

Figure 7 shows the implant machine with one implant specimen being tested and a second lying on the supporting plate at the left. The restraining clamp is employed to prevent potentially hazardous elastic rebound of the implant specimen when failure occurs.

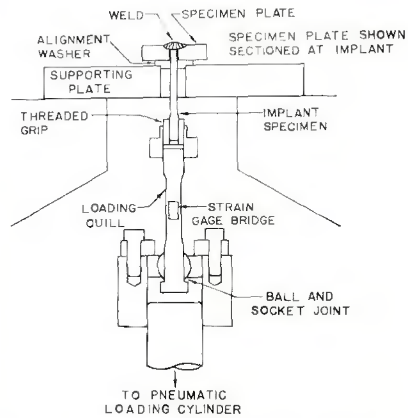

Fig. 6 — Details of implant machine

Table 2 — Mechanical Properties of Materials Used for Implant Tests

Material	Y.S., ksi	T.S., ksi	Elong. %[b]	Hardness, DPH[a]
HY-80 (Heat P)	88	108	25	239
HY-130	134	145	21	339
E10018	95	104	24	262
E14018	141	147	18	369
AX-140[c]	139	148	21	—

(a) 1 kg load — average of three readings.
(b) 1 in. gage length.
(c) Typical values for this material taken from producer's literature
Note: Weld-metal properties for 43 kJ/in. heat input.

Table 3 — Welding Conditions Used in this Investigation

	Process	Electrode diam, in.	Voltage, V	Current, A	Travel speed, ipm	Heat input, kJ/in.	Plate thick., in.	Preheat, interpass temp., F
E10018 weld pad	SMA	3/16	22-25	200-220	9	35	1-1/2	300
E14018 weld pad	SMA	3/16	22-25	200-220	9	35	1-1/2	300
Implant test	GMA[a]	1/16	29-31	290-310	12	48	1/2	75

(a) Gas flow 40 cfh of argon-water mixture obtained by bubbling argon through a 9-in. column of distilled water at room temperature.

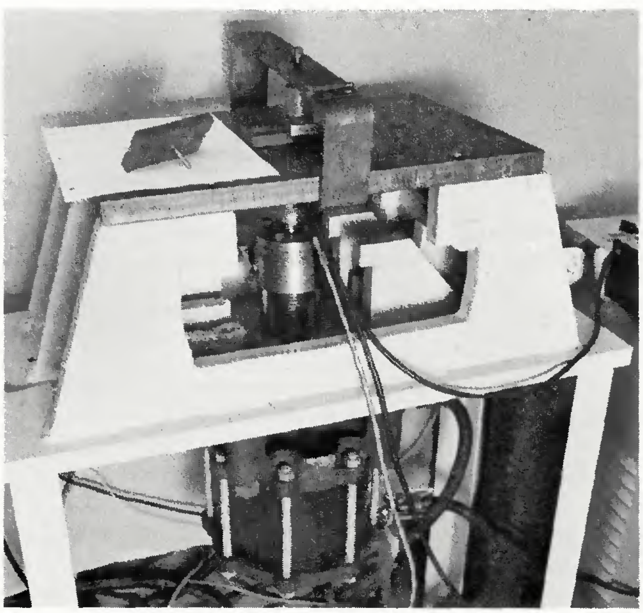

Fig. 7 — Implant machine showing an implant specimen on the left in addition to the specimen loaded under the restraining clamp

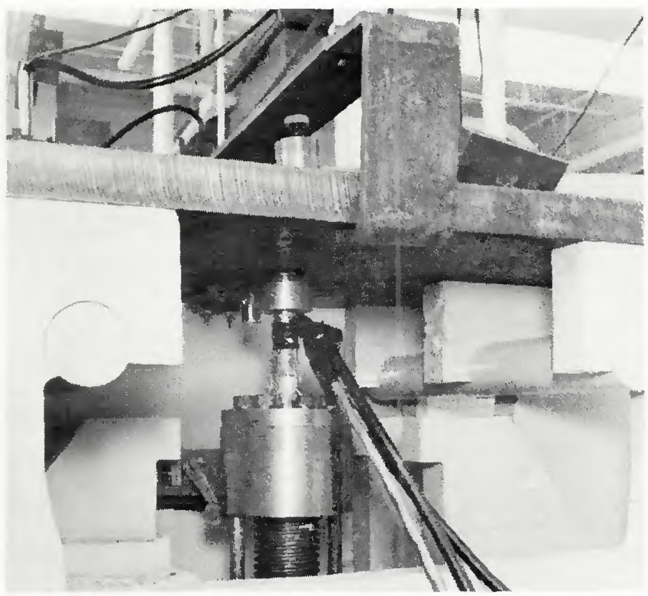

Fig. 8 — Close-up view of implant loading quill with the accelerometer immediately to the left and the cut-off switch at the lower left

Figure 8 is another view of the apparatus and shows the loading quill and the accelerometer used to monitor accoustical emission during the test.*

In order to insure that the specimens were all subjected to the same testing conditions, the following standardized procedure was used:

1. Assemble implant specimen in specimen plate** and clamp in the welding fixture.
2. Deposit the GMA test weld as indicated in Table 3.
3. Immediately after welding, remove the specimen plate from the fixture, air cool 3 minutes, and then invert in a tray of ice water with only the welded surface of the specimen plate immersed.
4. After 2 minutes, remove the specimen from the ice-water bath and load in the implant testing apparatus.
5. Apply the test load exactly 4 minutes after removal from the ice-water bath.
6. Record the load and any accoustical emissions during test (maximum test period, 24 hours).
7. The maximum stress level that a given test combination could sustain for 24 hours was taken as the lower critical stress (LCS).
8. The notch tensile stress (NTS) was taken as the stress required to cause failure in less than 1 second.
9. The time to rupture was measured by an interval timer actuated at the instant of loading and stopped by a microswitch on the loading quill when the specimen failed.

Results and Discussion

Results

Figure 9 shows the time to failure versus applied stress for both the HY-80 and the HY-130 steels when loaded parallel to the short transverse direction. Their notch tensile strengths were determined to be 133 ksi and 175 ksi, respectively, and their lower critical stresses were 67 ksi and 92 ksi, respectively.

From the data, the embrittlement indices were determined to be 0.47 for the HY-130 and 0.50 for the HY-80. Previous work has established that this heat of HY-80 is extremely crack sensitive (Ref. 19); therefore, it appears that the heats of HY-130 and HY-80 tested exhibit nearly the same relatively high susceptibility to hydrogen-assisted cracking.

Figure 10 shows the effect of specimen orientation in HY-130 on the constant-load rupture behavior. The data for specimens machined with their axes parallel to the short transverse (through plate thickness) direction indicate a slightly lower resistance to hydrogen-assisted cracking in this orientation. Note that the times to failure for the short transverse orientation are consistently shorter than those for the longitudinal orientation at the same stress level. Also note the lower value of LCS (92 ksi) for the short transverse than that for the longitudinal orientation (102 ksi). From these data, embrittlement factors of 0.42 and 0.47 are obtained for the longitudinal and transverse orientations, respectively.

Figure 11 compares the cracking susceptibility of E10018 and E14018 weld metals. Note that they both exhibit approximately the same LCS of 105 ksi, which is significantly higher than that of either the HY-80 or HY-130 studied (shown as dashed curves for comparison). However, the NTS for the E10018 is 135 ksi, compared to about 175 ksi for the E14018. The corresponding embrittlement indices are 0.22 for the E10018 and 0.40 for the E14018. These values indicate the E14018 weld metals to be nearly twice as susceptible to hydrogen-assisted cracking as the E10018 and appear to confirm the experience reported by users of these filler metals.

Figure 12 compares the constant-load rupture behavior for the HY-80 plate with that of the E10018. Note that, although the NTS is approximately the same for both, the HY-80 has a LCS of only 67 ksi compared to 105 ksi for the E10018 weld metal. In terms of embrittlement indices, this indicates the HY-80 tested ($I = 0.5$) to be over twice as susceptible to hydrogen-assisted cracking as the E10018 deposit ($I = 0.22$).

Figure 13 shows similar data for the HY-130 system. Again, the NTS values are nearly the same (175 ksi), and the E14018 shows a higher LCS than does the transverse HY-130. However, the difference is less significant than that shown by the E10018 deposit and the HY-80 plate.

The embrittlement index for E14018 is 0.40, which is only about 15% better than that of the HY-130 measured in the short transverse ($I = 0.47$) and a mere 5% better than that of the HY-130 measured in the longitudinal orientation.

Table 4 summarizes the results of the foregoing tests, and simplifies direct comparisons of material behavior.

Discussion of Results

From the data summarized in Table 4, one would predict that hydrogen-assisted cracking would be more likely to occur in the HY-80 plate than in the E10018 weld metal. The difference in sensitivity between this heat of HY-80 base plate and this lot of E10018 filler metal is so striking that heat-affected zone cracking could readily occur even though the hydrogen content of the weld metal tends to be higher than that of the heat-affected zone (where the hydrogen must be supplied by diffusion from the fusion zone).

In terms of the embrittlement indices, the HY-130 and this heat of HY-80, which has been shown to be a particularly crack-sensitive heat, are probably not significantly different in their crack susceptibility at this level of hydrogen (6.5 cc/100 g of deposited weld metal). However, in practice, the lower maximum moisture content specified for the E14018 electrode (0.1%) should result in a much lower level of hydrogen and, thus, the tendency for the HY-130 to experience cracking would be greatly reduced. On the other hand, although a weld in HY-80 should, with proper low-hydrogen practice, contain considerably less than 6.5 cc/100 g, the higher permissible moisture content (0.2%) would undoubtedly produce a hydrogen content in the HY-80 weldment nearly double that in a comparable HY-130 weldment.

Finally, the effect of using overmatching weld metal in the HY-80 system and not in the HY-130 system can not be ignored. An overmatching weld metal effectively increases the restraint imposed upon the crack-sensitive regions of the heat-affected zone immediately adjacent to the fusion boundary. Thus, even if both the weld geometries and externally imposed restraint were identical for welds made in the two systems, the over-matching weld metal in the HY-80 weldment can deform elastically at stresses that cause plastic flow in the weaker heat-affected zone.

Thus, cracking tends to occur in the weaker heat-affected zone of the HY-80, which is apt to be significantly less resistant to cracking than the E10018 weld metal, anyway. On the other hand, the E14018 weld metal and HY-130 appear to be so similar in both strength and cracking sensitivity that the location of cracking is likely to be wholly dependent on the local hydrogen content and the magnitude and orientation of the residual stresses. Since hydrogen enters the system via the molten weld pool and reaches the heat-affected zone only by diffusion, it is logical to expect the weld metal always to be richer in hydrogen than the heat-affected zone. All else being equal, then, it is probable that cracking would be more likely to occur in the weld metal, as has been reported to be the case (Refs. 2,4,5).

Therefore, the results of this investigation are consistent with the observations of others and indicate that the modified implant test shows promise

*The results of this portion of the investigation will be the subject of a second paper.

**2 × 4 × ½ in. HY-80, Heat P.

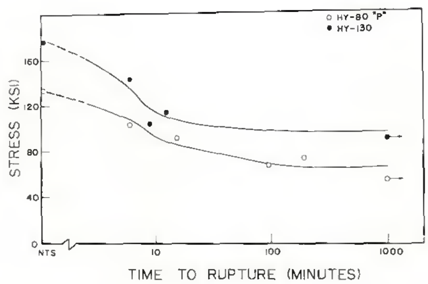

Fig. 9 — Test results of base metal implant specimens loaded in the short transverse direction

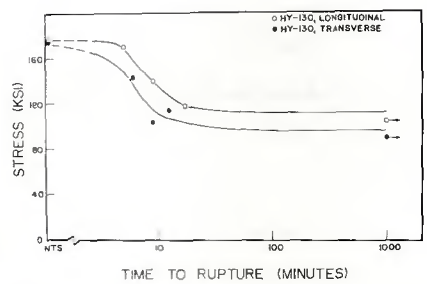

Fig. 10 — Test results of HY-130 implant specimens sectioned in the longitudinal and short transverse directions

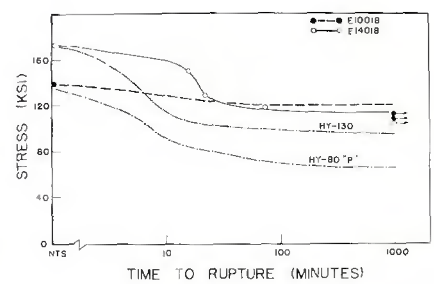

Fig. 11 — Test results of weld metal implant specimens

as a means for studying hydrogen-assisted cracking in high strength quenched and tempered steels.

Conclusions

1. The modified implant test with a helical notch proved to be sensitive to the differences in cracking susceptibilities of the materials studied.

2. The particular heat of HY-130 tested proved to have a susceptibility to hydrogen-assisted cracking similar to that of a highly crack-sensitive heat of HY-80.

3. The implant test results indicate that, for the same combination of stress intensity and hydrogen concentration, the HY-130 base metal studied is slightly more crack sensitive than the E14018 weld metal used in this investigation.

4. The implant test results indicate that, for the same level of stress intensity and hydrogen concentration, the HY-80 plate studied is over twice as sensitive to hydrogen-assisted cracking as the E10018 weld metal.

5. The implant test results show the HY-130 material to be slightly more sensitive to hydrogen-assisted cracking when loaded in the short transverse direction than when loaded in the longitudinal direction.

6. The implant test results indicate that the E10018 weld metal is nearly twice as resistant to hydrogen-assisted cracking as the E14018 weld metal.

Table 4 — Summary of Results of Constant-Load Rupture Tests of Implant Specimens

Material type	Orientation of loading	Short-time notch T.S., ksi	Lower critical stress, ksi	Embrittlement index, I
HY-80	Short transverse	133	67	0.50
HY-130	Short transverse	175	92	0.47
HY-130	Longitudinal	175	102	0.42
E10018	Short transverse	135	105	0.22
E14018	Short transverse	175	105	0.40

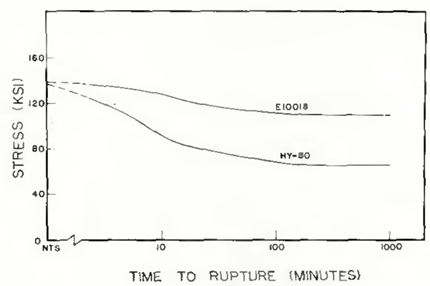

Fig. 12 — Constant-load rupture curves determined from E10018 and HY-80 implant specimens loaded in the short transverse direction

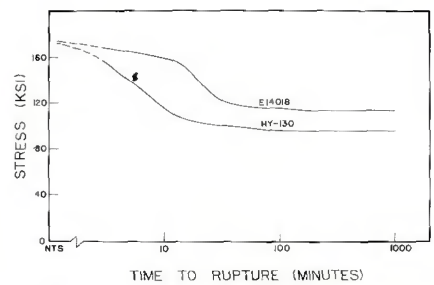

Fig. 13 — Constant-load rupture curves determined from E14018 and HY-130 implant specimens loaded in the short transverse direction

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"A Review of Bounding Techniques in Shakedown and Ratcheting at Elevated Temperatures"
by F. A. Leckie

"Upper Bounds for Accumulated Strains due to Creep Ratcheting"
by W. J. O'Donnell and J. Porowski

"A Review of Creep Instability in High-Temperature Piping and Pressure Vessels"
by J. C. Gerdeen and V. K. Sazawal

"Cyclic Creep — An Interpretive Literature Survey"
by Erhard Krempl

In recent years considerable effort has been devoted to developing a methodology based on detailed analysis to design structures which will operate under conditions of high temperature and periodic large thermal transients such that there exists a high level of confidence in their structural integrity. This methodology encompasses analytical methods, material behavior and design criteria. There has been excellent progress in all of these areas; however, it has become obvious that simplified procedures are needed, since the costs associated with performing a rigorous time-history analysis of a structure which is subjected to significant transient loadings while operating in the creep regime are very high, particularly if three-dimensional representation is required.

The Pressure Vessel Research Committee believes that progress in further developing this methodology will be assisted by the creation and wide distribution of a series of topical reports. This report series will serve to inform both by making available techniques and data which are relatively unknown in this country and by summarizing the current state of the art. In this manner the PVRC believes that technical progress can be stimulated and focused. However, the technology is in the developmental state and a full description of ancillary information is often not available (e.g., a complete description of the creep and plasticity response of a candidate material). Also, sufficient confirmatory experimental data on structures of similar geometries, materials and operating conditions does not exist for many of the proposed design methods such as those contained in the following report. Experimental programs such as those sponsored by the USAEC are expected to provide such confirmation and define the range of applicability of proposed methods. Thus the topical reports published in *WRC Bulletin 195* are not recommendations by the PVRC to industry on the appropriate technique for pressure-vessel design at this time, but rather are topical reports of the status of an aspect of elevated temperature design at a point in time to aid the current development work in this field.

For structures other than semi-infinite right circular cylinders of uniform thickness subjected to continuous internal pressure and cyclic radial thermal gradients, no closed form analytical methods of demonstrated conservatism exist. The use of finite element time-history analysis has proven to be, on occasion, extremely expensive. Thus a clear and urgent need exists for the development of simplified analytical techniques to permit the economic evaluation of potential ratcheting configurations.

The concepts discussed in these reports are expected to have significant value in reducing the analytical efforts for the design of elevated temperature structures. At the current time insufficient experimental data are available to permit the PVRC to endorse the techniques for bounding the response of potential ratcheting problems. Further experimental data on the basic response of candidate materials as well as ratcheting experiments on typical structures are required. These reports are recommended to the industry as a source of potentially valuable techniques. It is believed that these proposals deserve detailed examination and should be tested against the body of experimental data as it becomes available.

The price of *WRC Bulletin 195* is $11.00. Orders should be sent to the Welding Research Council, United Engineering Center, 345 East 47th St., New York, N.Y. 10017.