Discussion on "The Measurement of Crack Arrest Fracture Toughness in Welded 9% Nickel Steels Used in Cryogenic Storage Tanks"

Introduction

"The Measurement of Crack Arrest Fracture Toughness in Welded 9% Nickel Steels Used in Cryogenic Storage Tanks" by R. M. Bruscato was published in the Welding Research Supplement of the July 1981 issue of the *Welding Journal* on pages 113-s to 120-s.

The publication of the paper has since raised questions on the part of G. T. Hahn, R. G. Hoagland and A. R. Rosenfield* whose comments appear below under Discussion. Corresponding response on the part of R. M. Bruscato† follows under Author's Reply.

Discussion by G. T. Hahn, R. G. Hoagland and A. R. Rosenfield

Bruscato's (Ref. 1) recent experience in crack-arrest testing of 9% Ni steel generally parallels our own (Ref. 2) of several years ago. However, there are some significant differences. For this reason we would like to summarize our experiments in light of these newly-published data.

Both we and Bruscato used steel produced about a decade ago. Our experiments were confined to base metal which was 12.7 mm (½ in.) thick and had been heat-treated in accordance with ASTM A553-74. We used duplex double-cantilever-beam specimens, in which a notched block of high-strength/low-toughness steel (ASTM A517F) was electron-beam welded to the 9% Ni steel. The A517F served to initiate a rapid crack. Since crack-arrest data using this design on a nuclear reactor pressure-vessel steel agree well with those obtained using both of the designs in the paper under discussion (Ref. 3) for the same heat, there is no reason to expect differences due to test procedure.

As was the case with the Bruscato paper, we experienced considerable difficulty in propagating a rapid crack in 9% Ni steel. Since we observed dimpled rupture on a fractograph, we agree that the steel is exhibiting upper-shelf behavior despite the low test temperatures.

The major difference between our data and those reported by Bruscato is that we measured much lower values of K_a (stress intensity at arrest). In fact, the specimen that we tested at −164°C (−263°F) broke completely in two. In contrast, Table 1 of the paper under discussion reports either no initiation at this temperature or no penetration into the 9% Ni steel from the brittle weld bead used as a crack starter. At −196°C (−295°F), we measured values on three specimens of 59, 73, and 111 $MPam^{1/2}$. The average of these data is slightly more than half the average of Bruscato's data at the same temperature. The difference may be due to orientation since the ratio of K_a values between us and Bruscato is about equal to the ratio of transverse to longitudinal Charpy impact energies at −196°C (−295°F).

In contrast to the arrest data, our estimated K_c value at −196°C or −295°F (about 120 $MPam^{1/2}$) is close to the value suggested by Bruscato. Our value of K_D, the toughness associated with rapid crack propagation was 120–140 $MPam^{1/2}$, increasing slightly with increasing crack velocity. This behavior, termed rate-insensitive by Hahn et al (Ref. 4) is consistent with the observation of low measured K_a values provided crack propagation and arrest are treated as dynamic events.

In summary, our data do not support Bruscato's estimates of extremely high toughness values of early 1970's 9% Ni steel between the LNG temperature and the liquid nitrogen temperature, particularly if K_a is used as the toughness criterion.

References

1. Bruscato, R. M. 1981. The measurement of crack arrest fracture toughness in welded 9 percent nickel steels used in cryogenic storage tanks. *Welding Journal* 60 (7): 113-s to 120-s.
2. Hahn, G. T.; Hoagland, R. G.; and Rosenfield, A. R. 1976. *Dynamic crack propagation and arrest in structural steels.* Ship Structure Committee report SSC-256.
3. Rosenfield, A. R.; Jung, J.; Kanninen, M. F.; Markworth, A. J.; Marschall, C. W.; Milella, P. P.; Mincer, P. N.; and Shook, R. L. 1981. *Critical experiments, measurements, and analysis to establish a crack arrest methodology for nuclear pressure vessel steels.* NRC report NUREG/CR-1887, BMI-2071.
4. Hahn, G. T.; Hoagland, R. G.; and Cheverton, R. D. 1981. Crack arrest methodology for thick sections. *Advances in fracture research*, eds. D. Francois et al, 2: pp. 1043-1050.

Author's Reply

We thank the three authors of the above Discussion for their interesting comments concerning our work on welded 9% Ni steel. Their comments warrant additional discussion on the crack arrest testing of this steel and the measurement of K_a (the crack arrest fracture toughness) in this steel.

During the course of our work, we did attempt to compare our measurements of K_a for 9% Ni steel with other data, and we did attempt to compare our results with the Battelle results (Ref. 1) as well as the large amount of K_a results from testing recently conducted in Japan. For these various investigations, there were significant differences in testing techniques, interpretation of test results, and the 9% Ni test materials which make

Table D1—Summary of Test Results Reported by Tanaka and Associates (Ref. 4)

Thickness, mm (in.)	K reported at crack arrest,[a] MPa $\sqrt{m}$ (ksi $\sqrt{in.}$)			
	−162°C, i.e., −260°F		−196°C, i.e., −320°F	
32/33 (1.25)	210	(190)	200/220	(181/200)
27 (1.06)	250/285	(227/258)	180/280	(163/254)
16 (0.63)	550/630	(500/570)	200/640	(181/581)

(a) For most tests, the running crack arrested at interface between the crack initiation material and 9% Ni test material; consequently, the actual crack arrest toughness of 9% Ni steel is higher than the reported number.

*G. T. HAHN is associated with Vanderbilt University, Nashville, Tennessee; R. G. HOAGLAND is with Ohio State University, Columbus, Ohio; and A. R. ROSENFIELD is with the Physical Metallurgy Section, Battelle Columbus Laboratories, Columbus, Ohio.

†R. M. BRUSCATO is a Senior Engineer with the Metal Engineering Department, Chicago Bridge & Iron Company, Oak Brook, Illinois.

comparisons tenuous. Because it has an important bearing on the discussion by Hahn, Hoagland, and Rosenfield, we attempt to discuss and compare these results here.

Approximately 70 K_a type tests have recently been conducted in Japan using various versions of the Esso Test and the Double Tension Test. Many of these tests were conducted by Tanaka and his associates at the Nippon Steel Company; tests were also conducted by Mise and his associates at the Sumitomo Steel Company. A very recent paper by Kamath (Ref. 2) describes this testing. Testing was conducted on current production 9% Ni steel plate which can be expected to have higher toughness than our earlier vintage steel produced about 10 years ago. Based on the static crack initiation fracture toughness (K_c), it has been found that current production 9% Ni steel will exhibit up to 16% higher fracture toughness than earlier vintage steel (Ref. 3). As did we, the Japanese investigators had to utilize different crack initiator materials to provide the running crack to measure the crack arrest toughness in 9% Ni steel.

The test results from the work of Tanaka and his associates at Nippon Steel (Ref. 4) can be summarized as shown in accompanying Table D1.

Taking into account a higher fracture toughness of perhaps up to 16% in these 9% Ni steels (Ref. 3), these Japanese results at −162°C (−260°F) are in reasonable agreement with our estimate of $K_a > 225$ ksi $\sqrt{\text{in.}}$ (248 MPa $\sqrt{\text{m}}$) for 1 in. (25 mm) steel and much higher than our estimate of $K_a > 280$ ksi $\sqrt{\text{in.}}$) 308 MPA $\sqrt{\text{m}}$) for ½ in. (12.7 mm) steel. The results at −196°C (−320°F) are higher than our measurements of $K_a = 105/129$ ksi $\sqrt{\text{in.}}$ (116/142 MPa $\sqrt{\text{m}}$) for 1 in. (25 mm) 9% Ni steel and $K_a = 149$ ksi $\sqrt{\text{in.}}$ (164 MPa $\sqrt{\text{m}}$) for ½ in. (12.7 mm) steel.

Recent crack arrest testing has also been conducted by Nakano and his associates at the Kawasaki Steel Company (Ref. 5) where they used a hybrid Esso Test to measure crack arrest in 9% Ni steel. They utilized a high strength, low alloy steel (HT80), very similar to the A517F steel used by Battelle to produce a running brittle crack. One of the steels they tested was a moderate toughness heat of 9% Ni steel with Charpy properties and chemistry reasonably similar to our test steel. They reported the crack arrest toughness for the 22.5 mm (0.89 in.) plate at about 580 MPa $\sqrt{\text{m}}$ (526 ksi $\sqrt{\text{in.}}$) at −170°C (−274°F). This result is appreciably higher than our estimates of K_a.

In comparing our results to all of the Battelle results where seven arrest tests were conducted using the duplex double cantilever beam specimen (Ref. 1), and including the discussion by Hahn, Hoagland, and Rosenfield above, we note the following:

1. We concur that at −162°C (−260°F), 9% Ni steel purchased and tested to meet the requirements of ASTM A553 is on the toughness upper shelf.

2. It is interesting that in two of the Battelle tests, at −196°C (−320°F), the running brittle crack arrested at the interface between the A517F crack initiation material and the 9% Ni test material. In a third test at −152°C (−240°F), the running crack penetrated only 2.4 mm (0.095 in.) into the 9% Ni test material, where it arrested. Such behavior is similar to the behavior of our 9% Ni material in the Modified Compact Crack Arrest (CCA) test specimen where we could not propagate the running brittle crack from our crack initiator material into our 1 in. (25 mm) test material at −260°F (−162°C) nor in our ½ in. (12.7 mm) test material at −297°F (−183°C).

We think it is of interest that the CCA test specimen has been used by various researchers, including the discussors, to measure K_a in other steels at much higher temperatures (Ref. 6, 7). We too have conducted such tests with the CCA test specimen configuration similar to the one used on 9% Ni steel except that the E8018-C1 crack initiator weld bead was sharply notched rather than polished. Unlike the tests of 9% Ni steel where we could not propagate a running crack, neither we nor the other researchers had any difficulty propagating a running crack in the other steels in their ductile to brittle transition temperature range (Ref. 6, 7). We believe these other test results provide oblique but additional confidence in our K_a measurements in 9% Ni steel.

3. A fourth Battelle test was conducted at −164°C (−262°F) and was reported as a complete separation of the test specimen (i.e., the crack did not arrest in the test specimen). For this specimen the stress intensity at crack initiation was reported at 395 MPa $\sqrt{\text{m}}$ (359 ksi $\sqrt{\text{in.}}$) from a 0.57 mm (0.022 in.) radius notch in the A517F crack initiator material. This crack initiation stress intensity was from 152% to 400% higher than for the other six tests. It should be obvious that any test specimen (as well as any structure) can be made to fail if it is exposed to a high enough overload. From our tests, we were able to conclude that a running brittle fracture crack is not a viable failure mechanism for an LNG tank (−260°F, −162°C service temperature) fabricated with 9% Ni steel purchased to the requirements of ASTM A553 (Ref. 8). From this we strongly suspect that the failure mode for this fourth Battelle specimen was ductile rather than brittle. Indeed, the original Battelle work (Ref. 1) and the Hahn, Hoagland, Rosenfield discussion above point out that an examination of a fracture surface in their 9% Ni test steel revealed dimple rupture (i.e., a ductile fracture mode).

4. For the three remaining arrest tests which are described by the discussors, we note the following:

(a) The Battelle 9% Ni test material was described as "a commercially produced and heat treated 12.7 mm thick plate satisfying ASTM-A553" (Ref. 1). The chemistry and heat treatment reported (Ref. 1) are reasonably typical for 9% Ni steel produced in the early 1970's. However, on page 33 (Ref. 1), the steel is described as follows: "The Charpy data indicate that the heat treatment used on our experimental material produced the lowest toughness of any within ASTM A553". Unfortunately, no Charpy data are presented. Thus, it was not clear that the 9% Ni steel tested was 9% Ni steel as it is utilized in cryogenic tanks (i.e., meeting the Charpy requirements of ASTM A553).

In our work, leftover 9% Ni steel plate from actual cryogenic tanks was utilized, and we presented all the mill report test data on the specific plates we tested as well as our own Charpy data to verify that we were testing welded 9% Ni steel as it is utilized in cryogenic tanks. Although it was implied in our work, it was not specifically stated that the material orientation and crack propogation path duplicated actual tank conditions; this resulted in a L-T (longitudinal) testing orientation.

(b) An additional complication in evaluating and comparing the Battelle crack arrest results for 9% Ni steel was in reconciling their definition of crack arrest with their reported K_a values. Essentially, crack arrest toughness was defined as occurring when the toughness of a propagating crack (K_D) reaches a minimum. K_D was determined as a function of crack velocity (other factors such as temperature, metallurgical variables, held constant) so that the minimum toughness ($K_{D\,MIN}$) can be determined and thus the crack arrest toughness.

Such a measurement can be made for steel tested in the ductile to brittle transition temperature region where the dynamic toughness is less than the static fracture toughness and K_D can achieve a minimum value. But 9% Ni is in the toughness upper shelf regime at −260°F where the dynamic toughness is greater than the static toughness (Ref. 8), and this implies that rather than exhibiting a minimum value as a function of crack velocity, K_D will exhibit a maximum value. Indeed, the Battelle K_D data and the discussors point out that for their tests on 9% Ni, the toughness of the steel increased with increasing crack velocity and the highest K_D toughness at −196°C (−320°F) was measured for the highest velocity crack (Ref. 1). Under such conditions, we would expect that using the Battelle definition, $K_{D\,MIN}$ (and K_a) should approach the minimum toughness value for the 9% Ni steel, i.e., K_c. The Battelle results show, however, that while K_D does approach K_c at slow crack veloc-

ities, K_a is reported much lower than K_D or even K_c.

Summary

We do not know why some of the measurements of crack arrest toughness reported by the discussors (Ref. 1) are appreciably different than ours. We note that three of their tests seemed to duplicate ours in that a running brittle crack could not be induced in the 9% Ni test material. In another test, the specimen appeared to be overloaded so that its capacity to arrest the running crack was exceeded, and it appears that the fracture mode for this specimen was ductile, not brittle. Finally, for the remaining three arrest measurements, those results seemed to be inconsistent with the definition of crack arrest proposed by the discussors.

We tested welded 9% Ni steel as it is utilized in cryogenic tanks; we used current up-to-date K_a testing techniques which, over the last 3 or 4 years, have come to be the accepted and primary method for measuring K_a. Our results seem reasonably consistent or quite conservative compared to the many other measurements of K_a that have recently been conducted on 9% Ni steel. However, this is not surprising since virtually all of those tests were conducted on recent vintage 9% Ni steel which can be expected to exhibit somewhat higher fracture toughness. For one K_a test conducted on a steel similar to ours, a much higher K_a number was reported.

K_a testing of other steels at higher temperatures indicates that the CCA test specimen utilized in our tests on 9% Ni steel will easily produce a propagating brittle crack in those other steels. Clearly, if a test material, such as 9% Ni steel, does not propagate a running crack in the CCA test specimen, it must be due to the inherently high toughness of the test material; this, we believe, tends to confirm our K_a measurements on 9% Ni steel, albeit in an oblique manner.

References

1. Hahn, G. T.; Hoagland, R. G.; and Rosenfield, A. R. 1976. *Dynamic crack propagation and arrest in structural steels.* Ship Structure Committee report SSC-256.
2. Kamath, M. S. 1981 (Aug.) Crack arrest properties of 9% nickel steel at low temperatures, Part 1—test results (a). *Metal Construction:* 456.
3. Tobler, R. L.; Mikesell, R. P.; & Reed, R. P. Cryogenic effects on the fracture mechanics parameters of ferritic nickel alloy steel. *Fracture mechanics ASTM STP667:* 85-105. American Society for Testing and Materials.
4. Tanaka, K. 1981 (May). Data on fracture toughness characteristics of 9% nickel steel plate and its weldments. Presented at American Gas Association transmission conference session on Cryogenic Properties of Nine Percent Nickel Steel and Storage Tank Design Standards, Atlanta, Georgia.
5. Nakano, Y. Suzuki, S.; Kamada, A.; & Herose, K. 1981. Crack initiation and arrest characteristics of 9% Ni steels with various Charpy V-notch energy values. Presented at the International Cryogenic Materials Conference, Aug. 10-14, 1981, San Diego, California.
6. Hahn, G. T.; Hoagland, R. G.; Rosenfield, A. R.; and Barns, A. R. 1980. A cooperative program for evaluating crack arrest test methods. *Crack arrest methodology and applications ASTM STP 711:* 248-269. American Society for Testing and Materials.
7. Crosby, P. B., and Ripling, E. J. 1980. Significance of crack arrest toughness testing. *Ibid:* 321-337.
8. Bruscato, R. M. 1981. The measurement of crack arrest fracture toughness in welded 9% Ni steels used in cryogenic storage tanks. *Welding Journal* 60 (7): 113-s to 120-s.

WRC Bulletin 266
April 1981

Weldability and Fracture Toughness of 5% Ni Steel

Part 1: Weld Simulation Testing

by A. Dhooge, K. Ostyn, W. Provost, and A. Vinckier

This paper describes an investigation on the weldability of a double normalized and tempered 5% Ni steel using weld simulation to estimate the heat-affected zone (HAZ) ductility at cryogenic temperatures.

Charpy-V specimens were subjected to various weld simulation cycles and heat treatments and subsequently broken at a range of cryogenic temperatures.

Part 2: Wide Plate Testing

by A. Dhooge, W. Provost, and A. Vinckier

This paper describes the results of wide plate tensile tests on 25 mm thick welded 5% Ni steel plates in double normalized and tempered condition. The base metal and welded test specimens, containing 6 to 30 mm long through-thickness notches, were tested at temperature ranging from −90°C to −165°C.

Publication of this bulletin was sponsored by the Welding Research Council.

The price of WRC Bulletin 266 is $10.00 per copy, plus $3.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, 345 E. 47th St., Room 801, New York, NY 10017.