BRITTLE FRACTURE OF AMMONIA CONVERTER

High hardness adjacent to crack suggested vessel had not been given a final heat treatment; failure occurred during hydraulic testing

W. D. Clark
Imperial Chemical Ind.

K. G. Mantle
John Thompson, Ltd.
Wolverhampton
England

In December, 1965 this vessel failed on initial hydraulic test at the works of the makers, John Thompson Ltd., Wolverhampton, England, a two ton fragment being thrown 150 ft. The British Welding Research Assn. was commissioned by the makers to examine all relevant matters, and this report is based on their detailed report, which was published in full in the B W R A Bulletin, June, 1966.

The vessel was conventional, ten strakes 63 in. long, 67 in. i.d., 5.7/ 8 in. thick, electroslag welded and normalised, and then submerged-arc welded together and to a flat bottom forging and a 14 top flange forging. There were no side connections or other attachments. It was designed for 5,100 lb./ sq.in. at 120 C (250 F), and the test pressure was 6,950 lb./ sq.in. It failed at 5,000 lb./ sq.in. Design was on the lower of $\frac{\text{UTS cold}}{2.35}$ or 66.6% 0.2% proof at 120 C. On the ASME VIII code the vessel would have merited design and test pressures of 3,100 and 4,650 lb./sq.in.

The material was Colvilles Ducol W30 plate which has been used extensively in the U.K. and has a composition about 0.15%C, 0.2% Si, 1.3% Mn, 0.6% Cr, 0.25% Mo, and 0.80% V, and the forgings were similar, except that 0.20% C. was present by agreement. The forgings were in the normalised and tempered condition and a stress relief of the completed vessel at 620-660 C.(1150 1220 F.) was specified. The UTS was 81,000 / 92,000 lb./sq.in., the yield point 54,000 lb., and the elongation 20% minimum.

Failure initiated at two points in the HAZ of the top flange forging and destroyed this forging and the three adjacent strakes. There were five major fragments and some 150/ 200 ft. of cracking visible in the bore, much of which did not penetrate to the O.D. The vessel had been properly purged of air before the test, and the damage shows the dangers present in testing large HP vessels.

Two initiating cracks

The investigation showed that the failure had been initiated from two radial and longitudinal cracks about 3/16 in. x 3/8 in. at the forging side of the first circumferential weld, about 1/2 in. from the O.D. A third similar but unextended crack was discovered during examination. Such cracks are impossible to find by radiography and would only be found ultrasonically if the operator knew first where to look. The cracks were where a zone of segregates in the forging ran into the weld zone: these segregates were not obviously worse than might be expected in a 14 ton item from a 60 ton ingot, but the carbon content was assessed as 0.25% locally, and there was a concentration of sulphides. The hardness was locally up to 450 Vickers.

The failure occurred at a temperature of about 10 C.(50 F.). At this temperature the plate had 50 ft.-lb. Charpy V impact strength, the forging 30 ft.-lb. and the weld metal about 12 ft.-lb.

No final heat treatment

The high hardness adjacent to the crack suggested that the vessel had not in fact been given a final heat treatment of 6 hours at 640 C. as shown by the furnace charts: various tempering tests showed that the metal could not have been above 550 C. and might have been lower. Tests with thermocouples carefully attached to another vessel heat treated in the same furnace showed a major discrepancy between the 'recorded' and actual temperature, and indicated that the upper part of the vessel might have reached 630 C. for two hours, but the lower part probably only reached 520 C.

Chemical analysis of the weld metal, from the circumferential seam where the fracture initiated, showed an unexpectedly high chromium content, up to 1.5% compared with 0.7% obtained in the weld proceedure tests. This seam and the proceedure plates were welded by multipass submerged arc, using an alloyed flux. The reason for the discrepancy is, as yet, unexplained.

The low heat treatment temperature together with the high cromium content is believed to be the reason for the high hardness of the segregated areas and the poor toughness of the weld metal.

Both ASME and the British codes specify that the actual metal temperature shall be recorded: it seems clear from this investigation and other incidents that it is unusual to do this properly, and that there may be major discrepancies between different parts of the vessel.

The three cracks at the weld HAZ, one of which was not involved in the failure may have appeared during the pressure test or they may have appeared at any time after the weld was made. It is believed that they constituted a defect big enough to propagate in the hard HAZ around them, thus forming a defect big enough to cause propagation into the somewhat brittle weld metal, and the resultant crack was big enough to propagate through the parent plate, even though this was quite tough on a Charpy basis.

It was noted with interest that where the running cracks had crossed the longitudinal electroslag welds or the circumferential welds there was no sign of a tendency to crack along these welds.

What was concluded

The conclusions drawn are as follows:-

1. The failure was due to the presence of small cracks in a brittle region adjacent to weld metal which was also no tough. The small cracks were associated with minor segregates in a heavy

forging and were of a size below detection by normal N.D.T. methods. The brittleness was the result of inadequate heat treatment, segregates in the forging and a high chrome content in the weld metal.

2. There should be no relaxation from the requirement that the temperature of the actual vessel during heat treatment be measured at various points to ensure that every part is adequately treated.

3. Particular care is required if the vessel involves heavy forgings.

4. An impact strength of e.g. . 30 ft.-lb. Charpy V is quite inadequate to stop a crack running through 6 in. thick plate of this low alloy steel (or 2¼% Cr Mo steel - see NRL report 6030) and probably this is true for any ferritic steel.

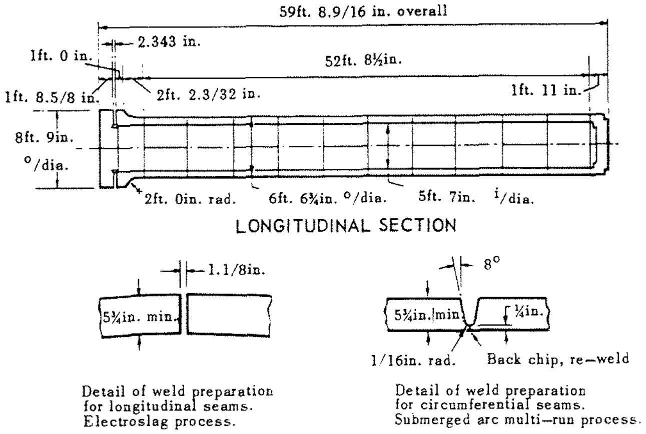

Figure 1. Details of vessel which ruptured.

5. It is believed that had the test been done at a higher temperature - e.g. 60 C. (140 F.) - the vessel would not have failed so disastrously, and it would be good practice to test all heavy vessels at temperatures well above the minimum temperature permitted by the code (ASME 60 F., U.K. B.S. 1,515 7 C.).

6. Once the vessel has reached its test pressure it would not fail at lower applied stresses.

7. While failures of vessels during pneumatic testing can be highly dangerous, hydraulic testing of large high pressure vessels is also somewhat hazardous.

NOTE: A replacement vessel was put in hand immediately following the failure, and this was successfully hydraulically tested on the 9th.

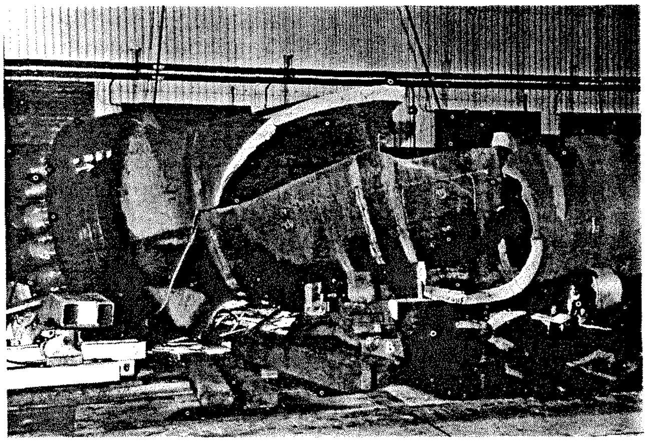

Figure 2. Closeup of vessel after it ruptured.

Discussion

Q. Did you conclude that you got a precipitation in hardening in the heat affected zone to cause the loss of ductility in the material?

Mantle: Yes, definitely. The figures were running up to something over 400 vickers.

Clark: If I could comment on that. The so-called stress relieving heat treatment given to many vessels does two things. First, it reduces residual stresses from the welding with which engineers are familiar, and secondly, it tempers the steel.

When you weld a low alloy steel, you are liable to end up with a quite high hardness adjacent to the weld. If it is too high, the metal may crack on cooling. The welding procedure with such steels must be controlled carefully to avoid such cracking, but may even so leave quite a hard zone. The stress relieving operation also tempers that zone and makes it soft. It was because of the hardness in the region of these cracks being so high, that this was the proof positive that the stress relieving temperature had not been what was recorded on the chart.

If I might comment on what Mr. Sorell has said, I wonder if he would agree with me that once you have got a vessel through its pressure tests, you will not have a brittle failure of that vessel under the same stresses. In other words, if you raise the stress in the wall of a vessel to 50,000 lb./sq.in. at 60 F, or whatever temperature you would like to do a pressure test, that vessel will not fail brittle if you put it up to 49,000 lb./sq.in. at 0 F., or maybe a much lower temperature. This is the present opinion held pretty strongly in England that once you have subjected a thing to a certain level of stress, you need not fear brittle fracture at any lower stress level.

The controlling factor is, however, not pressure, but stress, since there are many forces operating on vessels and piping additional to the pressure. On subzero equipment contraction stresses in piping can add to the stresses near vessel nozzles. If the combined stress exceeds that induced in the pressure test, then brittle fracture is entirely possible at pressures below the test pressure.

I know of at least one large company, with American associates, but not ICI, which uses the ASA Piping Code for all its piping but for sub-zero piping it halves the allowable stress range in the Code for thermal stresses at butt welds etc. I would be much interested in Zeis' comment on that point.

The other point which I would like to make is this. Zeis talked about impact testing and transition zones. I felt that he was painting a picture which was black or white, that a vessel was either brittle or it was ductile. I think there are a very, very large number of vessels which live in a twilight zone - vessels which will serve for years perfectly safely but if they get a kick in any way, then they will fly to pieces in a brittle manner.

Mr. Zeis discussed the Charpy test as a method of selecting tough steels. There is much argument about the exact criterion, but few people would not accept 35 ft.lb. at the operating temperature. Now one of the most important points in my view on the failure of the Thompson converter is that at the failure temperature, the shell plate had over 50 ft. lbs. Charpy V value and it became riddled with cracks. There was about 200 feet of cracking, much of it far from any areas where there were special stresses, and this is a clear demonstration that Charpy V values normally suggested give no protection against brittle fracture. There are many other tests available, but it is doubtful if any test costing less than say $1500 on thick plate, and taking less than a month to do, is of much value. The Charpy test can weed out substandard material of a given type, but little more.

L. A. Zeis (M. W. Kellogg Co., Inc.): In regard to Mr. Clark's question about hydrostatic tests. I believe he suggested that if any vessel has passed a hydrostatic test, that it can then be safely subjected to the same stress at a lower temperature. There are certainly many cases where this has worked in the past. We know that many pressure vessels are in service at temperatures lower than the hydrostatic test temperature. We should not take too much assurance from this, because of the following point concerning defect size raised by the previous questioner.

This reference to the Naval Research Laboratories' research points out that defects of a certain size can be safe for a given stress level. This mechanism has been proven valid by Pellini's tests and by many tests on high strength materials. For the normal range of carbon steels, the critical size of defect for the stress level used is of such dimension that it will be detectable by nondestructive tests. When the critical size of defect is small, as in higher strength steels, or the thickness is great, the critical defect may not be detected.

Getting back to Mr. Clark's question, assume that a vessel has passed the hydrostatic test in the presence of defects X-thousandths long. The defects may not be safe at some lower temperature. A defect which would be harmless at 40 F may not be harmless at -300 F even though both temperatures are below the transition temperature. We can be reasonably sure that if a carbon steel vessel were stressed at -300 F, this pressure test would find a defect large enough to propagate.

The second question with regard to the transition temperature and the Charpy V-notch test is related to the fracture mechanics research which we didn't feel we should discuss today. This approach relates critical defect size, material sensitivity at temperature and stress level. This same approach could be correlated with Charpy V-notch energy. It appeals to us because it is a simple test, it is fast, and it is economic. There has been some recent work which indicates that if a sample at test temperature absorbs half the maximum energy, it will be safe at test temperature. For example, if samples from a given plate absorbed 80 foot pounds at 100 F and 80 foot pounds at 150 F, then it would be safe for normal loading conditions if a sample absorbed 40 foot pounds at service temperature.