FRACTURE SAFETY ASSESSMENT OF EXPLOSION CONTAINMENT VESSELS IN HIGH AND LOW STRENGTH STEELS

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Charpy, Dynamic Tear, Drop Weight NDT, and dynamic K_{Jc} data are presented for BS1501-151-28A plate, weld, and forging, and for HY80 manual and submerged arc weld. The significance of the data is discussed in the context of a particular design of explosion containment vessel.

INTRODUCTION

The vessels considered in this report are fabricated by joining two hot pressed hemispheres with a circumferential girth weld. A forged nozzle is attached to one of the nozzles by a second circumferential weld. The vessel is approximately 30 mm thick with an outside diameter of 950 mm.

A series of these vessels was made for use in an experimental test programme. Early examples were built in a normalised Carbon pressure vessel steel, BS1501-151-28A. In a subsequent move to increase the load capacity of the vessels, and to provide a greater measure of fracture assurance, a change was made to the use of a quenched and tempered Ni-Cr-Mo steel, HY80. For the BS1501 vessels all welds were made using the submerged arc (SA) process with manual (MMA) root runs. This procedure was also used for the HY80 vessel girth weld, but the HY80 nozzle weld was made using an exclusively manual process. BS1501 vessels were stress relieved after fabrication, but the HY80 vessels were used in the as-welded condition in accordance with the normal practice for this steel, which is susceptible to temper embrittlement if cooled too slowly through certain temperature ranges.

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This report highlights the problems encountered in comparing the fracture performance of two such different fabrication systems. In particular the difficulty of adequately characterising the fracture resistance of the HY80 weld metal.

The vessels had a required minimum operating temperature of +10°C.

EXPERIMENTAL DATA

Mechanical property tests were conducted on specimens extracted from test plates manufactured by the vessel fabricators. Data on BS1501-151-28A forging was obtained by cutting up a spare vessel nozzle. HY80 plate and forging material was not tested extensively except to ensure that the minimum specified yield of 550 MN/m^2 and Charpy energy of 100 Joules at -84°C were met. The specified toughness of HY80 is so high as to guarantee that the parent material will be fully ductile at +10°C. Attention for the HY80 vessels was thus focussed on the properties of the weld metal. (Charpy tests were used to show that the HAZ properties were not a problem in either fabrication route).

Notch orientation in all BS1501 plate specimens was LT (although it was not expected that orientation effects would be very important after the hot pressing and normalising production route). For the BS1501 forging the notch orientation was CR (where C is circumferential and R is radial). This was chosen from consideration of the likely principal stress direction in the nozzle. The BS1501 weld was through notched. The HY80 weld specimens, which were in the as-welded state, were surface cracked (TS) to avoid complications associated with precompression. This orientation also has the advantage of simulating the configuration of most concern for structural defects.

Tensile data. Static tensile data for all the materials tested are shown below.

TABLE 1 - Average Tensile Properties of Materials Tested.

Vessel Type	Material	0.2% Proof MN/m^2	UTS MN/m^2	Elongation %	R of A %
BS1501-151 -28A	plate forging weld	235 270 365	430 500 465	39 35 37	68 62 76
HY80	plate weld (MMA) weld (SA)	590 685 525	700 760 660	32 28 28	80 67 72

Charpy data. Charpy transition data are compared in Figure 1.

Dynamic Tear. 16 mm Dynamic Tear tests were conducted in accordance with (1). The test is conceptually similar to the Charpy, but uses a larger specimen containing a sharp pressed notch to give a more precise indication of structural brittle to ductile transition temperature under dynamic loading. Results are summarised in Figure 2.

Drop Weight NDT. P3 size drop weight NDT tests (2) were conducted on BS1501 plate (NDTT = -10^{o}C) and HY80 welds (NDTT = -65^{o}C for the MMA weld and -80^{o}C for the SA weld).

Dynamic K_{Jc}. Pre-fatigue cracked bend and compact tension toughness tests were carried out on a high rate servo-hydraulic machine with load and crack mouth opening displacement being monitored. Time to unstable fracture, or to a stable maximum yield plateau, was less than 5 msec. Compact tension specimens were used to test the BS1501 plate, forging, and weld. Bend specimens were used for the HY80 weld. Compact tension specimens were slightly below the structural thickness with B = 25 mm, W = 50 mm, and a/W = 0.5. For the forging, which was of variable thickness, some tests were also conducted on specimens with B = 50 mm, W = 100 mm, and a/W = 0.5. Results fell in the same scatter band as the 25 mm specimens. The HY80 weld bend specimens were made the full thickness of the weld test panel with B = W = 34 mm and a/W = 0.3. Results in terms of K_{Jc}, where $K_{Jc} = \left[J_cE/(1 - \nu^2)\right]^{\frac{1}{2}}$, are plotted in Figure 3. Unless otherwise stated J_c is calculated at a fracture instability point. The method used to calculate J from the load and clip gauge data follows that in (3). A few tests were also performed on HY80 weld bend specimens with very shallow cracks (0.06 < a/W < 0.15). These are discussed later in the text.

FRACTURE MECHANICS ANALYSIS

The best indication of brittle fracture risk in the vessels is provided by the dynamic K_{Jc} tests. These employ a fatigue sharpened notch in a specimen which closely matches structural thickness and loading rate. Data in Figure 3 shows that, at the minimum proposed operating temperature of +10^{o}C, both the BS1501 and HY80 submerged arc weld metals were fully ductile, with very high upper shelf toughness values. The BS1501 plate and forging, and the HY80 MMA weld are all in their brittle to ductile transition region with K_{Jc} between 100 and 200 MNm$^{-3/2}$. Critical defect sizes associated with this toughness level can be obtained by fracture mechanics analysis.

The R6 method (4) provides a particularly convenient method of combining fracture and plastic limit load analyses on one assessment diagram. A defect length of 120 mm was chosen for the analysis to provide a convenient value for the shell parameter employed in the various stress intensity and plastic limit load formulae used in the analysis, and also as a realistic estimate of the maximum length of defect likely to be in the vessels. Toughness levels employed were 145 $MNm^{-3/2}$ for the BS1501 plate and HY80 weld, and 95 $MNm^{-3/2}$ for the forging. The BS1501 vessels were required to sustain a peak explosive pressure equivalent to a membrane stress of 235 MN/m^2. The HY80 weld metal is analysed both for this applied stress and for a doubled pressure loading equivalent to a stress of 470 MN/m^2. In addition, the HY80 weld metal was assumed to contain residual stresses comprising a net restraint moment peaking at half yield stress in tension on the inside of the vessel, plus a self-equilibrating distribution peaking to half yield at both surfaces. Small defects on the inside of the vessel were thus assumed to be subjected to yield point tensile residual stress. Dynamic yield stress for the BS1501 plate (345 MN/m^2) and forging (400 MN/m^2) was inferred from the limit load of dynamic compact tension specimens performed in the temperature range 25°C to 50°C. The validity of this approach was confirmed by a static test on the BS1501 plate at ambient temperature which indicated a yield of 235 MN/m^2, in exact agreement with the static tensile result. This method could not be used for the HY80 MMA weld since all the specimens tested failed before general yield. The dynamic yield was conservatively assumed to be no higher than the static value of 685 MN/m^2.

Figure 4 shows the results of the R6 analysis for the three materials under consideration. Critical defect depths at +10°C for a 120 mm defect length are 20 mm for the BS1501 plate, 17.5 mm for the BS1501 forging, more than 20 mm for the HY80 weld metal at 235 MN/m^2, but only 2.5 mm for the HY80 weld metal at 470 MN/m^2. Failure in the BS1501 plate is plastic limit load dominated, whilst that in the HY80 weld is brittle fracture dominated. The BS1501 forging lies in an intermediate region. The reduction in K_r with increasing crack depth in the HY80 weld metal arises from the rapid reduction in residual stress away from the inside surface where the defect is assumed to be located.

OTHER FRACTURE AVOIDANCE METHODS

Charpy, Dynamic Tear, and Drop Weight NDT indices for the HY80 manual weld are all superior to those for the BS1501 plate and forging. Table 2 lists safe operating temperatures predicted by

TABLE 2 - Results of some Empirical Fracture Control Methods

Method	Reference Index	Minimum Safe Temperature °C			Comment
		BS1501-151-28A		HY80 Weld	
		Plate	Forging		
AFNOR NFA 36-010 (5)	Charpy energy	-26	-20	-39	Based on equations in section 3.3 of (5)
BS5500 (6)	Charpy energy	+5			Safe temperature for static loading with shift of +70°C
Lange (7)	Dynamic Tear energy	+15	+30	-10	
Pellini (8)	NDTT	+20		-5	From 'K_{1D} design curve' with required toughness set at 80 $MNm^{-3/2}$ for BS1501 plate and 165 $MNm^{-3/2}$ for HY80 weld

some empirical fracture control methods based on these indices. BS5500 is based on correlation with Wells Wide Plate test data. All the other methods rely on correlation between the stated index and plain strain dynamic toughness, K_{1D}. Applied loadings are static yield for (5), dynamic yield for (7), and four times yield strain for (6). None of the methods with the exception of (6), which is only applicable to carbon and carbon manganese steels,distinguishes between as-welded and stress relieved structure. In (8), two toughness levels which seem appropriate to dynamic yield stress loading have been selected for use with the recommended K_{1D} design curve.

The 70°C shift used in conjunction with (6) was derived by comparing static and dynamic K_{Jc} data on BS1501-151-28A plate.

Assumptions on crack size vary between the methods; being smallest for (5) - 8 mm through crack or 3 mm deep by 30 mm long surface crack - and largest for (7), through crack length in excess of 30 mm.

Broadly, the results for the BS1501 vessel can be said to be consistent with the fracture mechanics analysis conclusion that the vessels are safe at ambient temperature. The results for HY80 are, however, in contrast to the fracture mechanics analysis, in that the HY80 vessels are in all cases predicted to be safer than the mild steel vessels. All the empirical methods predict the HY80 vessels to be fracture-safe below 0^oC at stresses up to the static yield of the weld.

DISCUSSION

The anomalous conclusions to emerge from the analyses above are a reflection of the very different fracture characteristics exhibited by the BS1501 parent material and the HY80 weld. This can be illustrated by looking at the K_{Jc} traces and fracture faces in Figures 5 and 6. (A K_{Jc} trace for the HY80 SA weld is shown for comparison in Figure 7). Initiation toughness for unstable fracture is the same for both the BS1501 forging and the HY80 manual weld, but crack propagation in the forging is completely brittle, with little evidence of shear lip and an instantaneous fall in load whereas in the weld, significant shear lips are developed, and the load falls only gradually as the crack propagates through the ligament.

Charpy energy, Dynamic Tear energy, and Drop Weight NDTT are all dependent to a large extent on the energy absorbed during crack propagation. A weld metal may exhibit low initiation toughness but still have good crack propagation resistance. Low initiation toughness can be ascribed to the presence of isolated patches of brittle, as-deposited weld metal; while good propagation resistance arises from the surrounding matrix of tough grain refined material.

Most fracture-safe design methods are based on avoidance of fracture initiation. It is not easy to quantify the advantage of using a material with good crack propagation resistance. The fracture mechanics calculations suggest that the operating stress of the HY80 vessels should be limited to no more than that of the BS1501 vessels because of the poor initiation toughness of the manual weld. Clearly, however, if a crack did initiate, there is much more chance of it arresting without causing significant damage in the HY80 vessel than in the BS1501 plate and forging.

Previous work on HY80 weld metal (9) has shown that there can be a significant increase in K_{Jc} with decreasing crack depth. Confirmation of this for the manual weld tested here is shown in Table 3. These results call into question the very small critical crack depth of 2.5 mm calculated for the HY80 weld at 470 MN/m^2. This was based on a K_{Jc} of 145 $MNm^{-3/2}$, compared to a K_{Jc} of more

TABLE 3 - Dynamic K_{Jc} Results at 10°C for HY80 Manual Weld as a Function of Crack Depth. † Indicates Stable Maximum Load Toughness

a/W	0.31	0.30	0.15	0.11	0.08	0.06
K_{Jc} $MNm^{-3/2}$	149	186	382	560	651	998†

than 500 $MNm^{-3/2}$ when a defect of this a/W is tested in a laboratory bend specimen. Although the loading in the structure contains a membrane tension component not reproduced in the bend specimen, more than half of the K_r value applied to the structural defect comes from residual stresses, which are assumed to fall off very sharply from the weld surface. Unfortunately, this notch depth effect on toughness is not yet understood sufficiently to be deployed with confidence in the fracture analysis of a critical component.

In practice, it was decided to remove any possible doubts about the fracture safety of either the HY80 or BS1501-151-28A vessels by increasing the operating temperature to +30°C. This could be achieved, without undue inconvenience, by a modest preheating of the vessels. This, combined with other precautions, such as extensive NDE and proof testing, was considered to fully guarantee the fracture integrity of the vessels up to 235 MN/m^2 for BS1501-151-28A and up to 470 MN/m^2 for HY80. For further HY80 vessels, a change was made to submerged arc welding of the nozzle as well as the girth weld. This ensured that the vessels could be used at ambient temperature without any risk of brittle fracture.

CONCLUSION

The fracture safety of a particular design of explosion containment vessel has been examined. Vessels made from a low strength normalised carbon steel BS1501-151-28A have been found to have adequate initiation toughness, but rather poor crack propagation resistance. The advantages of using an alternative fabrication route employing a quenched and tempered low alloy steel, HY80, are reduced by the poor initiation toughness of the manual weld metal as measured in a dynamic K_{Jc} test. The low dynamic initiation toughness of this weld metal could not be predicted from Charpy, Dynamic Tear, and Drop Weight NDT tests; the results of which reflected the weld's good crack propagation resistance. Fracture control procedures based on these indices are likely to be unconservative for HY80 welds in applications where fracture initiation from large cracks must be avoided. On the other hand, qualitative observations of the weld's good crack propagation toughness, and of the increase in initiation toughness with decreasing crack depth, suggest that there are considerable reserves of safety when conventional fracture mechanics analysis methods are applied to this type of weld.

SYMBOLS USED

a = crack depth (mm)

B = specimen thickness (mm)

E = Young's modulus (MN/m^2)

J_c = value of elastic-plastic crack tip characterising parameter J calculated from load and clip gauge displacement at unstable fracture (MN/m)

K_{Jc} = value of J_c in stress intensity units ($MNm^{-3/2}$)

K_r = applied stress intensity normalised by K_{Jc} used in R6 method

K_{1D} = plane strain dynamic toughness ($MNm^{-3/2}$)

S_r = applied stress normalised by plastic limit load stress used in R6 method

W = specimen depth or width (mm)

ν = Poisson's ratio

MMA = manual metal arc

NDTT = nil ductility transition temperature

SA = submerged arc

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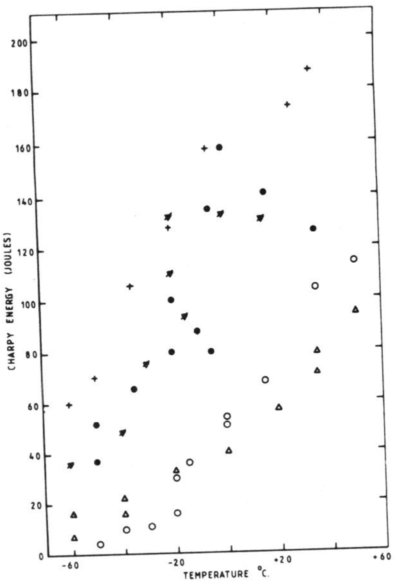

Figure 1. Charpy data

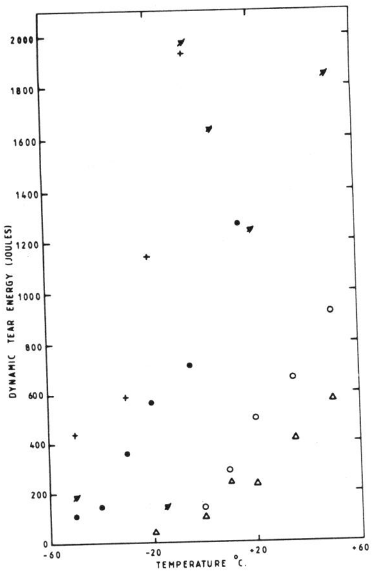

Figure 2. Dynamic Tear data

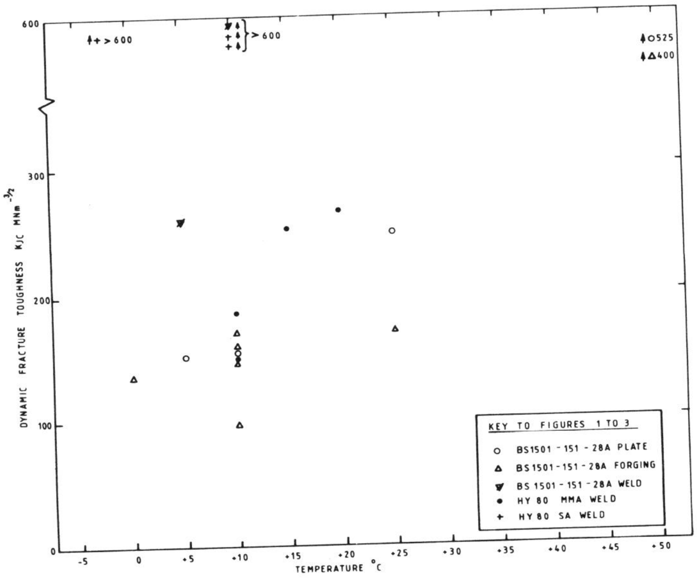

Figure 3. Dynamic K_{Jc} data

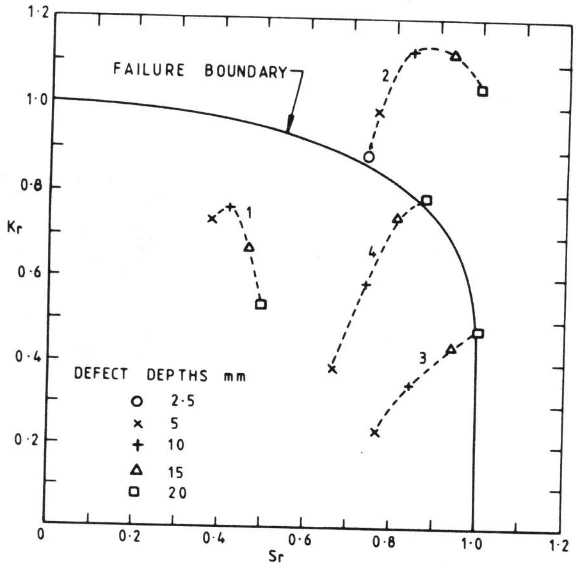

Figure 4. R6 Analysis: 1,HY80 weld 235 MN/m^2;2,HY80 weld 470 MN/m^2;
3,BS1501 plate; 4,BS1501 forging

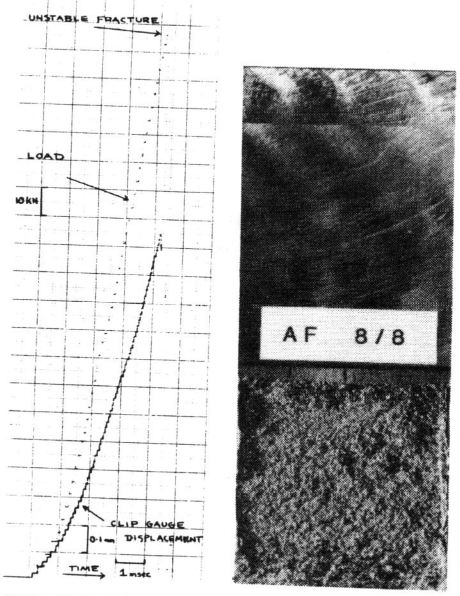

Figure 5. BS1501-151-28A forging, dynamic K_{Jc} trace at +10^{o}C

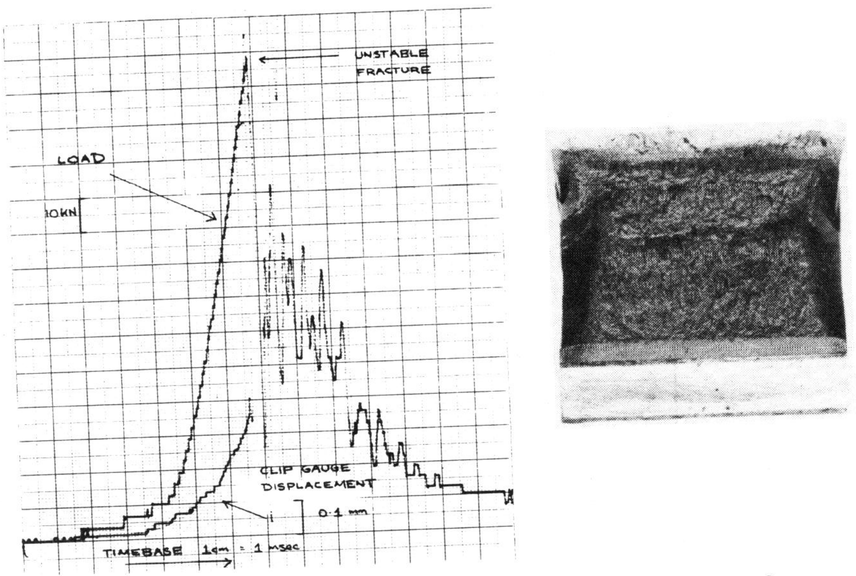

Figure 6. HY80 manual weld, dynamic K_{Jc} trace at +10°C

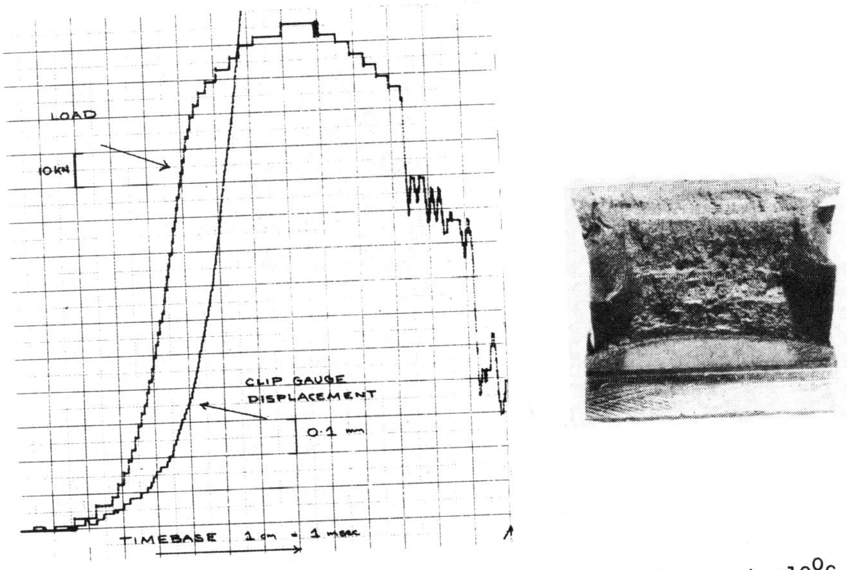

Figure 7. HY80 submerged arc weld, dynamic K_{Jc} trace at +10°C