BRITTLE AND DUCTILE FRACTURES IN SERVICE OF PRESSURE VESSELS

Nada Filipovic*, Katarina Geric **
* Welding Institut, Belgrade, S&CG, email :zzz@ bitsyu .net
**Faculty of Technical Sciences, Trg D.Obradovica 6, Novi Sad, S&CG,

ABSTRACT

Two tinn-walled pressure vessels of the same thickness (8 mm) exhibited different behaviour at failure. It has been shown that the failure of an underground storage tank for liquefied natural gas during first proof pressure testing with liquid nitrogen is a consequence of a brittle fracture. Due to overloading and a steadily increasing temperature, a mobile storage tank for the transportation of ammonia was destroyed by a ductile mechanism. In both cases, although they exhibited different fracture mechanisms, the crack was initiated in the heat-affected-zone of the weld joint.

Introduction

The analysis of failure of two pressure vessels revealed that, due to environmental condition, the fracture mechanisms was quite different, brittle in the first one (Case I), and completely ductile in the Case II, although the base metal of both vessel was of the same thickness and sufficient specified ductility.

The Case I refers to the fracture of an underground storage tank for liquified natural gas, made of fine grain steel, of 9.96 m^3 in volume. The results, obtained in testing performed prior to the first pressure proof test (properties of the base metal, ultrasonic testing, radiographic control of the welded joints) met the required welding and vessel quality. Nitrogen in a gaseous state, brought from a tank where it is kept in a liquid state, was used for the proof pressure testing. The maximum pressure was 25 bar (service pressure 16,7 bar). An explosion occured during the proof pressure test, and the tank was destroyed.

The second case (Case II) refers to the fracture of a mobile storage tank for ammonia transportation, made of microalloyed high strength steel, 4 m^3 in volume. The tank was manufactured in accordance with the strict requirements for the quality level for mobile storage tanks for liquid and under pressure dissolved gases. The explosion of tank occurred after 18 years of satisfactory service. Measurements have shown that the mobile storage tank in the critical situation was overcharged, by 20 kg of medium more than the maximum allowed quantity. An increase of the temperature during the course of the day resulted in an increase of the pressure of stored gas, which caused plastic deformation, bulging, wall thickness reduction, and the final failure of the tank by ductile collapse.

The results of performed analysis and investigation of these failures will be presented.

Material and welding

The 8 mm thick vessel mantle in Case I was produced from structural steel S355J2G3 according to EN 10025, with the chemical composition given in Table 1, and mechanical properties presented in Table 2. The microstructure exhibited expressed banding and non-uniform distribution of pearlite, with secondary linear structure, sulfide inclusions and segregation. The ferrite grain size was 9 -10, according to JUS C.A3.004 (Fig. 1a).

Table 1. Chemical composition of S355J2G3 steel (Case I)

C	Mn	Si	P	S
0.2	1.5	0.5	0.013	0.007

Table 2. Mechanical properties of S355J2G3 steel (Case I)

Tensile strength, R_m	Yield strength, R_{eH}	Elongation, A_5	Impact energy
MPa	MPa	%	J
540	395	30	39

In Case II, the vessel mantle of the same thickness (8 mm), was manufactured of normalized Nioval 470 steel, with chemical composition shown in Table 3, and mechanical properties presented in Table 4. The base metal is characterized by laminated ferrite pearlite microstructure with fine grains. Ferrite grain size was 12, according to ASTM (Fig.1b).

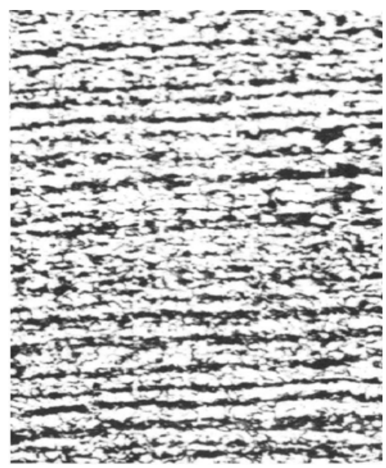
Table 3. Chemical composition of Nioval 47 steel

C	Mn	Si	P	S	Cr	Ni	V	Al	Ti	Nb
0,16	1,52	0,41	0,006	0,006	0,11	0,12	0,07	0,06	0,001	0,035

Table 4. Mechanical properties of Nioval 47 steel

Tensile strength, R_m	Yield strength, R_{eH}	Elongation, A_5	Impact energy
MPa	MPa	%	J
635	520	21	135

a. S355J2G3 steel (Case I)



b. Nioval 47 steel (Case II)

Figure 1. Microstructures of investigated steels

Circumferential and longitudinal welded joints of the mantle of the underground storage tank for liquified natural gas (Case I) had been performed by combined welding procedures. Two root passes had been welded applying inert gas shielding procedure with tungsten electrode (GTAW), and filler passes were performed by metal manuel arc welding with coated electrode (SMAW). Impact toughness was determined by sub-sized specimens (cross section 5x10 mm). The obtained average values of impact energy in coarse grain region of HAZ was 23 J, and 27 J in the weld metal, satisfying the specificatiton.

The microstructure of the base metal is not homogeneous due to laminated pearlite, as it is visible on the macrograph of the welded joint, Fig. 2. The HAZ microstructure is coarse grain beinite with acicular ferrite inside austenite grains and proeutectoid ferrite in net forms on austenite grain boundaries, Fig 3. Inclusions and coarse austenite grains in the HAZ favoured the occurance of acicular ferrite. The proeutectoid ferrite in the austenite grain boundary is very coarse and brittle, and is therefore prone to brittle fracture.

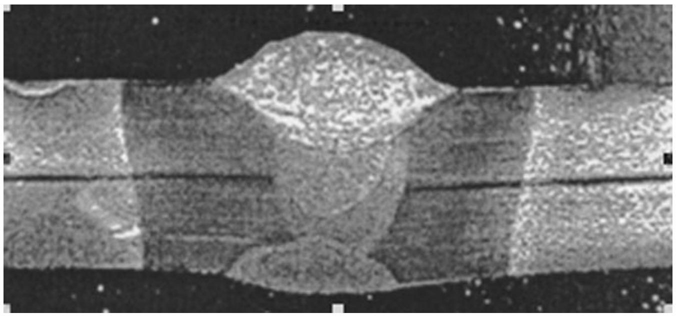


Figure 2. Macrograph of the welded joint - S355J2G3 steel

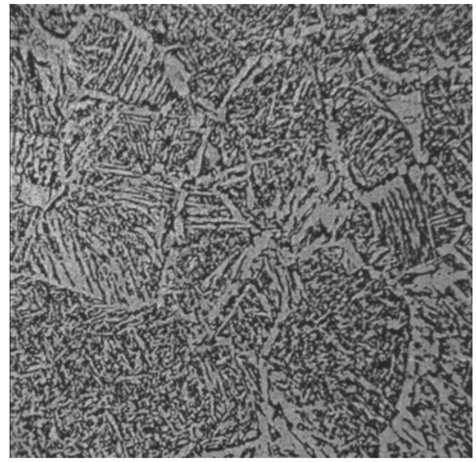


Figure 3. Coarse grain zone in HAZ (Case I).

Welding of circumferential and longitudinal welded joints of the mantle of second vessel, mobile storage tank for ammonia transportation, was performed in two passes by submerged arc welding (SAW), one from each side. The fillet welds of the tank supports to the mantle were welded by SMAW.

The circumferential welded joint is of beinite ferrite microstructure with a coarse net of proeutectoid ferrite on the prior austenite grain boundaries. The ferrite beinite microstructure had been found in the heat-affected-zone.

Fracture Analysis

The view of the underground storage tank for liquified natural gas after brittle fracture is presented in Fig. 4. The plastic collapse of the mobile storage tank for ammonia transportation, with visible bulging, is presented in Fig. 5. In both tanks, the crack initiated in the heat-affected-zone (HAZ) of the vessel mantle. In the Case I, after initiation crack propagated in the longitudinal vessel direction, perpendicular to the circumferential welded joints. In Case II crack propagated following the circumferential welded joint.

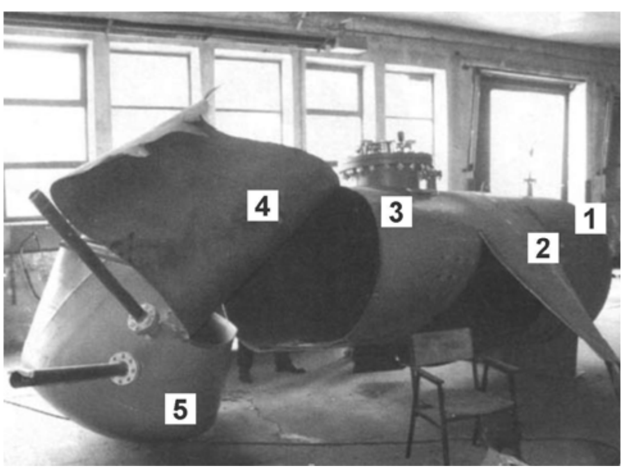


Figure 4. Brittle fracture of the underground storage tank for liquified natural gas (Case I)

Figure 5. Ductile fracture of the mobile storage tank for ammonia transportation (Case II)

In Case I, the crack occured in the lower part of the vessel mantle. From the lower part, one small piece of material was punched out, Fig. 6. The crack initiated in the HAZ of the circumferential welded joint, Fig. 7, in the coarse microstructure of the final bead (Fig. 3), then on one side partly propagated perpendiculary to the longitudinal vessel axis, along the HAZ of circumferential welded joint located in position 2 of pressure vessel (Fig. 8). Reaching the region of higher toughness in welded joint, crack devited into the base metal, in which it was finally arrested. On the other side crack propagated longitudinally through the base metal. In position 3 of the vessel (Fig. 9), after initiation in HAZ, crackdid not follow HAZ, but propagated through the base perpendicularly to the weld, and where it was again arrested.

Figure 6. Fracture on the lower part of the underground storage tank

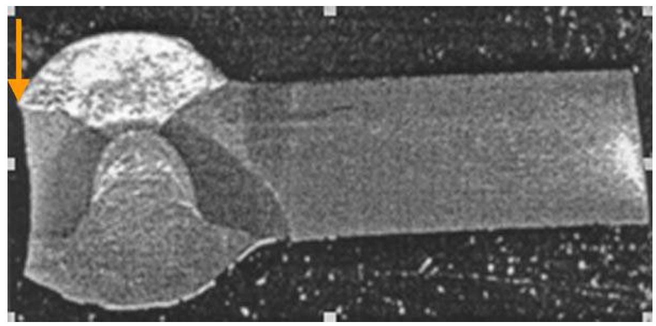


Figure 7. Crack initiated and developed through the HAZ of underground storage tank

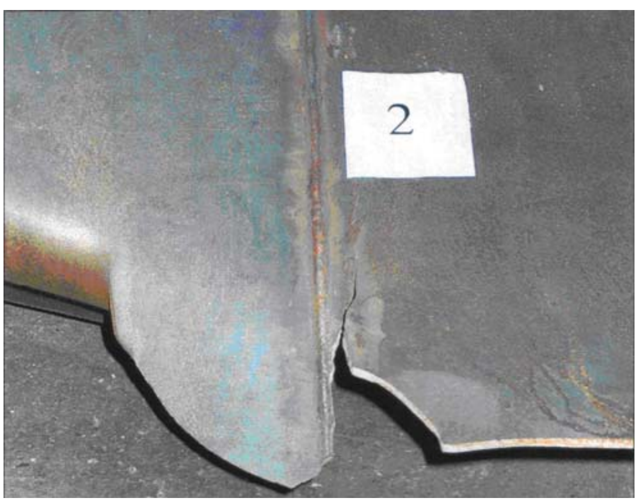


Figure 8. Crack deviated from the HAZ to the base metal

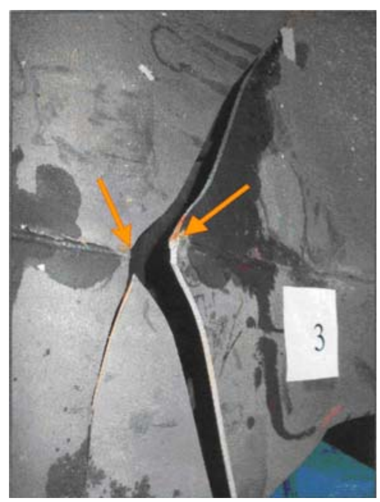


Figure 9. Crack deviated from the HAZ to the base metal

Analysis of the fracture surface on both the left and right sides of the point of initiation, along the heat affected zone, revealed that the fracture surface is perpendicular to the surface of the vessel, and flat, which is typical for the brittle fracture, without plastic deformation, (Fig. 10). The chevron patterns, which can be easily recognized in Fig. 10, could followed back eventually indicate the position of crack initiation, After normal flat fracture surface, corresponding to brittle fracture, the separation process had been finished by shear mechanisms in plane stress condition, in the slant direction of maximum shear stress acting in 45° direction, as it is shown in Fig. 10 for vessel position 2, and more clear in Fig. 11 for position 3, with typical brittle to ductile transition of fracture, with shear leaps.

Figure 10. Fracture surface with chevron pattern

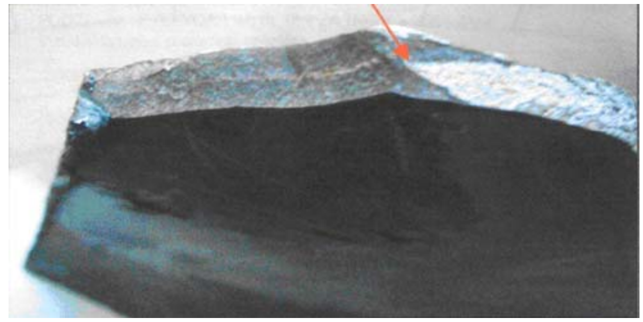


Figure 11. Chevron patterns

In the mobile storage tank for ammonia transportation (Case II), the crack initiated in the HAZ of the fillet weld between the mantle and the support reinforcement, firstly propagated longitudinally, in the direction of the vessel axis, and finally in the direction perpendicular to the axis of the vessel (Fig. 5). The point of initiation was located in the region where plastic deformation was constrained, Fig.12, which corresponds to plane strain condition. On the fracture surface 1 mm deep undercut can be seen, at the begining of the fillet weld. The crack then propagated in the base metal in the highest hoop stress direction, Fig. 13. Propagation of the crack was through the circumferential weld by shear mechanisms.

Analysis of the fracture surface has shown ductile fracture, followed prior plastic deformation. Scanning electron microscopy revealed the fibrous fracture [2], the crack growth through the thickness in the form of half ellipse crack. Shear leaps are typical for growing cracks in this case, and the slant fracture surface is inclined by 45°, in the direction of maximum shear stress.

Figure 12. Location of crack initiation with indicated crack developement path

Figure 13. Macrograph of fillet weld with undercut causing strain concentration and plastic collapse

Figure 14. Shear mechanisms with shear leaps

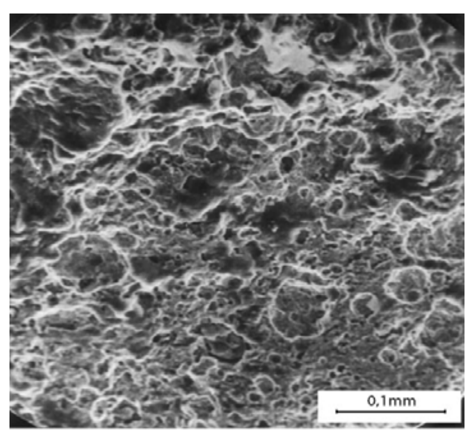


Figure 15. Ductile fracture surface

Discussion

In both cases, the properties of the base metals were in accordance with the required quality. The impact energy for the HAZ and weld metal were in accordance with the standards, but 20 to 25% lower than for the base metal, which is acceptable. The coarse structure and the lower impact energy value are probably why the crack initiated in the coarse grain HAZ. The HAZ is very often the weakest point in a welded joint, especially in high strength steels [1].

In Case I of the underground storage tank, according to the procedure, during proof pressure testing with gases from a higher pressure source, the material of the vessel should not be cooled below the nill ductility temperature (-20 ˚C in this case), and in order to be in accordance with the procedure, should be 25°C above it. It is supposed that during the proof pressure test, the underground storage tank had been exposed to the temperature lower than the nill ductility transition temperature, and the initiation of the britlle crack in plane strain situation can be attributed to this testing condition. The point of initiation in the lower part of the storage tank is expected, because that part is exposed to the lower temperature than the upper part of the tank. Crack propagation is parallel with the vessel longitudinal axis, according to the direction of maximum hoop stress. After some time, because of reduced temperature, the mantle temperature increases, and next propagation of the crack was ductile, with shear fracture surfaces at an angle of 45°, corresponding to maximum shear stress and plane stress condition.

In Case II, mobile storage tank for ammonia transportation fractured in fully ductile manner. Wall thickness reduction was from 8 mm to 5.3 mm at the point of crack initiation. The measured hardness of the HAZ on the mantle plate was from 310-321HV5, which is acceptable according to standard EN288-3, but having in mind the working medium (ammonia), due stress corrosion the recommended maximum value of hardness was 250HV. Because of the high value of toughness of the base metal, and the coarse grain of HAZ, the crack was propagating through the HAZ.

Conclusion

Regardless of the quality of base materials and performed welded joints satisfying specified quality level, the described typical fracture examples occurred due to dissregarded technical regulations. The fracture was in one case the result of improper proof pressure testing, and in the other case a result of overloading. The cracks in both tanks initiated in the heat affected zone tank mantle, as the HAZ is the most critical location due to the presence of brittle structures with low toughness.

Despite the materials from which the vessels were manufactured was of the same thickness, in general corresponding to plane stress condition, in one case the fracture was brittle and in the other case fracture was fully ductile. The different types of fracture were the consequence of the different environmental conditions in which it occurred.

References

1. Gerić, K., Prsline u zavarenim spojevima – Monografija, (Cracks in welded joints – Monograph), FTN Izdavaštvo, Novi Sad, (2005).
2. Metals Handbook ASM, Vol.9, Metals Park Ohio