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INSPECTION, NON-DESTRUCTIVE TESTS AND REPAIR OF WELDED PRESSURE EQUIPMENT

INSPEKCIJA, ISPITIVANJE BEZ RAZARANJA I REPARACIJA ZAVARENE OPREME POD PRITISKOM

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Keywords
- non-destructive testing
- pressure equipment
- crack
- welded joint

Abstract

Safety of pressure equipment in exploitation is of great importance and needs to be at a high level. Recently, this goal is achieved by implementing years of experience into regulations and standards, along with developing and improving materials, technologies and test methods for manufacturing and exploitation of pressure equipment.

Methods for designing pressure equipment typically involve calculations which do not take into account defects within the material that can lead to crack initiation, which in turn can result in failure. Methods described in this paper focus on crack behaviour and its relation to the type and amount of present defects in the material.

Experience suggests that, despite high demands for pressure equipment quality, failures can still occur in exploitation. In order to avoid this, pressure equipment should be tested in exploitation. In addition, adequate documentation needs to be developed in order to provide a basis for defining these tests.

It can be seen that pressure equipment failures are caused only by cracks. Other types of defects do not lead to failure directly, but may cause crack initiation. Thus, exploitation tests are mainly focused on cracks, while taking into account other defects that could lead to their initiation.

Ključne reči
- ispitivanje bez razaranja
- oprema pod pritiskom
- prslina
- zavareni spoj

Izvod

Bezbednost u radu opreme pod pritiskom je od velike važnosti i mora biti na visokom nivou. Danas se može reći da je ovaj cilj ostvaren implementacijom višegodišnjeg iskustva u propise i standard, u kombinaciji sa razvojem i unapređenjem materijala, tehnologija i metoda ispitivanja opreme pod pritiskom tokom proizvodnje i rada.

Metode konstruisanja opreme pod pritiskom do sada su se zasnivale na proračunima koji nisu uzimali u obzir prisustvo grešaka u materijalu, koje mogu da dovedu do pojave prslina, što može da prouzrokuje otkaz. Metode opisane u ovom radu se fokusiraju na ponašanje prslina i njihovu povezanost sa vrstom i brojem grešaka prisutnim u materijalu.

Iskustvo je pokazalo da, uprkos zahtevima vezanim za kvalitet opreme pod pritiskom, i dalje postoje otkazi opreme tokom eksploatacije. Kako bi se ovo izbeglo, neophodno je opremu pod pritiskom ispitivati tokom eksploatacije. Osim toga, potrebno je napraviti odgovarajuću dokumentaciju koja će poslužiti kao osnova za definisanje ovih ispitivanja.

Otkazi opreme pod pritiskom su isključivo posledica prslina. Druge vrste grešaka ne dovode direktno do otkaza, ali mogu dovesti do pojave prslina. Stoga, ispitivanja u eksploataciji su najviše fokusirana na prsline, imajući u vidu i druge vrste grešaka koje mogu dovesti do njihove pojave.

INTRODUCTION

Nowadays it can be said with great certainty that the safety of pressure equipment in exploitation is at a high level. If this safety is assessed as the ratio of the number of failures in exploitation to the total number of pressure equipment units of various types in exploitation, then it can be concluded that the risk of catastrophic failure is reduced below 10^{-6} per year of exploitation, /1/, which suggests a very high level of safety of pressure equipment in exploitation. This is achieved by implementing lot of experience into regulations and standards and by developing materials, technologies and control methods in manufacture and exploitation.

Classic methods of designing pressure equipment are based on calculations which take into account working stresses, strength characteristics and material plasticity, corrosion addition, safety factors and to an extent on the fact that structural materials do not have the same properties in all directions. These methods do not consider the fact that materials contain defects that could lead to crack initiation and that, during exploitation of pressure equipment, can result in various damage, that can also become location of crack initiation. During exploitation of pressure equipment with cracks that occurred due to defects or damage, these cracks can start growing. This growth is initially slow and stable until a critical length is reached, at which point it starts developing at a much greater rate, quickly leading to failure.

Experience suggests that, despite strictly defined demands in terms of pressure equipment quality and compliance of these during development and exploitation, there is still a possibility of failure. This is confirmed by numerous practical cases where after a number of years in exploitation, failures have occurred, e.g. the leaking of the main natural gas pipeline in Serbia, natural gas pipeline explosion in Siberia, leaking of the wagon tank used for ammonia transport, leaking of spherical tanks, destruction of amine absorbers in an oil refinery /2/. For the purpose of avoiding this, tests have been prescribed for pressure equipment in exploitation. Regulations require that the manufacture of all types of pressure equipment is followed by the development of documents that contain data on the quality of materials used, competence of the staff involved and the quality of welded joints. These documents represent an important base for defining test procedures for pressure equipment in exploitation.

From the above it can be concluded that pressure equipment failures can only be caused by cracks. Other types of material defects cannot cause failure directly, but could lead to crack initiation. Due to this, cracks are the main focus of exploitation tests, followed by other defects that could lead to their initiation.

PRESSURE EQUIPMENT SAFETY

Pressure equipment safety in exploitation depends on the safety of its weakest spot. In order to assess the safety, it is necessary, in every actual case, to determine the weakest spot in the equipment, determine its properties and assess its behaviour during further exploitation.

Safety assessment of welded pressure equipment includes a global and local approach. Global approach represents a classic calculation of basic dimensions along with a proper selection of geometry while assuming material homogeneity. This alone does not provide insight into pressure equipment safety. There is also a need to include numerous additional data related to equipment detail geometry, used materials, development technology and exploitation conditions. Shape, i.e. detail geometry, can result in different stress state compared to those predicted by the basic dimension calculation. Development technology causes, more or less extensive, local changes in parent material properties. In order to assess pressure equipment safety, material properties need to be known for these changed areas as well, along with their size, position and behaviour in exploitation conditions. This represents a local approach to pressure equipment safety.

Welded joints represent a heterogeneous material consisting of the parent material, heat affected zone (HAZ) and weld metal. The HAZ itself consists of numerous structures with varying properties. Properties of the welded joint depend on the chemical composition of parent and additional material, initial state of the parent material and the amount of heat input during welding. This heat affects the amount of molten metal, the volume of the liquid bath, additional material transfer conditions, degree of metallurgical reaction completeness and crystallization conditions. In the HAZ, the amount of heat input conditions, the formation of different structures, therefore resulting in smaller or greater differences in the properties of these zones, compared to the parent material.

All welded joints contain defects, regardless of welding quality. Defects can be classified as metallurgical – technological and subjective examination defects. Metallurgical – technological defects include cracks, pores, inclusions and deviations from required material properties. Subjective defects include lack of fusion, porosity, undercuts, overlaps or incomplete penetration, etc. With the development of new welding technologies, the amount of defects in welded joints is reduced. However, defects are an integral part of welded joints and it is not realistic to expect a welded joint without defects.

Of particular importance are cracks as the most hazardous form of defects. It is known that a certain number of pressure vessels ended their work life with cracks in welded joints, without failure, /3/. From this, it can be concluded that some cracks do not jeopardize pressure vessel integrity. For a reliable safety assessment of pressure equipment with cracks, it is necessary to know the characteristics of the crack and the material surrounding it, as well as the working conditions. Standards require the removal of all detected cracks. However, it is unrealistic to assume that all cracks can be detected, especially micro-cracks. Therefore, pressure equipment can reach the end of its life with cracks, unless the conditions for its critical growth are fulfilled.

As can be seen, numerous reactions take place during welding, in both liquid and solid state, more or less complete, which result in the occurrence of zones with different structures, dimensions and properties, along with the occurrence of different defects with different shapes and positions. Therefore, during the design and manufacture of welded joints, a number of variable and often unknown factors emerge which significantly reduce the possibilities for predicting the behaviour of the zones within the welded joints and of all defects within it, compared to predicting the behaviour of the parent material. Due to this, welded joints represent the critical locations in pressure equipment and are the primary focus of exploitation tests, /3/.

Welded joints are not necessarily the only critical locations in pressure equipment. Elements used for manufacturing pressure equipment such as casts, forgings, sheets and pipes can contain cracks or other defects that can lead to crack initiation or propagation. These elements may also have inadequate mechanical or technological properties, e.g. inadequate corrosion resistance or poor weldability, which also contributes to crack initiation. In these cases, such elements also become critical locations in pressure equipment. Best insight into quality and properties of pressure equipment can be obtained from certificate documentation which is a part of the Document collection for pressure equipment. Reports on previous exploitation tests can also be of aid. Certificate documentation and the results of previous tests can be used to determine whether or not the pressure equipment contains defects and if this equipment is repaired or reconstructed in-service. These locations need to be the focus of visual inspection and non-destructive tests (NDT) if necessary.

During exploitation tests of pressure equipment, not all welded joints are fully examined. Instead, welded joints where the highest tensile stress occurs, are selected for NDT. Such welds are required to be of highest quality and require most extensive NDT. This approach is incorporated into regulations related to the manufacture and testing of pressure equipment, /4, 5/. In addition, welded joint tests should also include locations where defects are repaired during the manufacture of pressure equipment, locations of defects detected during exploitation tests and welded joints made during equipment repair. Data from the Collection of documents and results of previous exploitation tests can provide insight into this information. Before NDT, a visual inspection of welded joints in pressure equipment should be performed in order to check the compliance between the documentation and the on-site situation, and based on this examination and documentation, critical locations should be defined. Visual inspection can be used to define additional critical locations in pressure equipment, e.g. locations of arc ignition in the parent material, locations of stress concentration (overlap, undercut) or locations with frequent defects, which are usually not evident in the documentation.

After testing and determining the state of critical locations in pressure equipment, it should be assessed whether detected defects jeopardize further safe exploitation. In case this is true, defects must be removed which can be achieved by repairing or restoring. Repairing involves the removal of the defect and the material containing it, whereas restoring also involves the returning of the repaired location to its initial measures by surfacing or welding. Procedures for repairing or restoring pressure equipment must always be in accordance with regulations and contain within itself a procedure for determining the quality of the repaired/restored location, along with the procedure for assuring the safety of the pressure equipment in further service.

PRACTICAL EXAMPLES

In the following section, several examples of exploitation tests of pressure equipment with cracks are shown. Test and repair procedures are described, and in certain cases the causes of crack initiation are analysed, along with the procedures for additional control repaired or restored locations.

Cracks in the revision opening flange

Figure 1 shows cracks detected in the flange of a revision opening in a tank during its exploitation tests, /6/. Cracks are detected by visual inspection and penetrant tests.

The tank is cylindrical, horizontal, heat isolated, with a diameter of 1600 mm, total length of 7180 mm and volume of 12.5 m^3 and is used for storing of liquid carbon-dioxide. Mantle and lid are made of micro-alloyed steel P460NL1 (NIOVAL 47), with a thickness of 14 mm, and the flange is of high-alloyed austenitic steel X10CrNiMo18.10. Lowest working temperature of the tank is –55°C, the highest working pressure is 30 bar, and the test pressure is 39 bar. The tank is a Class II pressure vessel, according to standard JUS M.E2.151, which was valid when the tank was manufactured and tested.

For the purpose of the exploitation test of the tank, a procedure is defined according to which visual inspection should be followed by ultrasonic test of mantle and lid wall thickness, magnetic and ultrasonic tests of welded joints in the mantle, whereas the welded joint between the flange and the lid should be ultrasonic tested and by penetrants. All welded joints in this case should be tested 100%. After these tests, the tank is tested using internal water pressure, and subsequently, non-destructive tests are repeated on all welded joints in the same way as they have been previously performed.

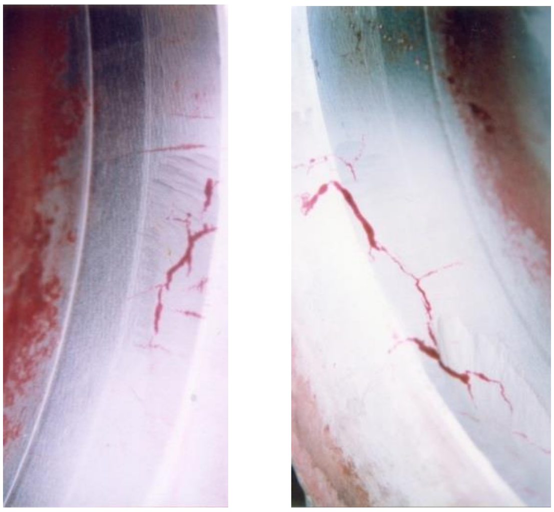

Figure 1. Cracks in the revision opening flange.

Figure 1 shows that the attempt to remove cracks by grinding results in the reduction of their number and/or size. The nature and causes of the occurrence of these cracks are not studied here. Due to a large number of cracks and their significant depth, it is decided to cut out the flange and replace it with a new one. For the purpose of welding the new flange, a technology recommended by the tank manufacturer in the Collection of documents is used. In this way, the time required for tests is reduced, along with the costs, since the classification of the welding technology for the flange is avoided. Regulations for manufacturing welded pressure equipment require use of non-destructive and destructive methods in order to prove that the welding technologies used for this equipment provide welded joints of sufficient quality.

The flange and the weld which connects it to the tank are again tested using NDT after the tank is tested using internal water pressure, and no defects are detected.

Transient crack in the austenitic flange of a manhole opening

During the testing of a tank using internal water pressure, drops of water are detected on the outer side of the wall of a manhole opening flange, /7/. The tank had the same characteristics as the one described in the previous section. Additionally, the same procedure for exploitation tests is recommended. The manhole opening consists of a mantle of steel P460NL1, of thickness 10 mm, welded to the tank lid on one side, and the flange on the other side, whereas the flange is of austenitic steel X10CrNi18.10. This welded joint and adjacent zones, both in the flange and the manhole opening mantle, are visually inspected and tested using penetrants. These tests reveal a mesh of cracks in the flange, near the welded joint. Water drops are clearly visible in some of these cracks, suggesting the cracks are passing through the entire thickness of the flange wall.

All cracks are located in a clearly defined zone which starts at about 3 mm from the weld metal fusion line and ends on the transition from the cylindrical to the conical part of the flange neck. Cracks are oriented in the general direction of the manhole opening axis. Crack concentration, along the welded joint circumference varies, ranging from very high to isolated cracks. In the high concentration area, the cracks are intertwined and form a mesh. Figure 2 shows the cross-section through the centre of the zone with highest crack concentration, /8/. As can be seen in the figure, a large number of cracks are perpendicular to the flange neck surface. Cracks propagated to various depths, some of them passed through the entire wall thickness.

In terms of geometry, number and position, detected cracks are reminiscent of damage that occurs in austenitic steels due to intercrystal corrosion. However, since the outer side of the flange is not in contact with the corrosive medium, but with air, there are no conditions for the development of intercrystal corrosion. Hence it is assumed that cracks occurred due to some sort of brittleness, which is a characteristic for the steel X10CrNi18.10.

Figure 2. Cracks in the cylindrical part of the austenitic flange neck of a manhole opening, /8/.

Chemical composition of the flange is given in the quality certificate, provided by the tank manufacturer as part of the Collection of documents. From this certificate it can be seen that the steel has high C content and that it does not contain stabilising elements such as Nb and Ti. Heating of this steel during welding at temperatures below 900°C results in the separation of δ-ferrite and brittle phases such as carbides $(Cr,Fe)_4C$ and the intermetallic compound FeCr – σ phase. Separation of these microconstituents is particularly intense in the temperature range of 450-850°C and in the case of steel X10CrNi18.10 it is initiated within less than a minute at these temperatures, /9/. From the above it can be concluded that, along with the welded joint, a zone with separate brittle phase could appear. The width of this zone depends on the width of the zone in which the material is heated to temperatures between 450 and 850°C longer than one minute. This means that the brittle phases will not separate in the part of the heat affected zone between the fusion line and the line where the temperature is above 850°C. Carbides are mainly separated along the austenite grain boundaries in form of a broken mesh. With an increase in temperature and heating time, carbides first form a continuous mesh along grain boundaries, and then begin to separate within the austenite grains as well.

Positions of zones in which the separation of brittle phases within the HAZ of the austenitic steel is expected, as well as those in which it is not expected, match the position of zones in which cracks are and are not detected during the testing of the welded joint between the flange and the manhole opening mantle. Based on this, it can be assumed that crack initiation is related to the occurrence of brittle phases, especially carbides.

Tests have shown that, in the zone with highest crack concentration, all cracks are located within clearly defined boundaries and they all are oriented in the general direction of the tank axis. It is assumed that the crack growth mechanism is as follows: microcracks are formed around carbide inclusions. Under the effect of tensile stress, ‘bridges’ of austenitic material between carbide inclusions extend and break, causing the microcracks to connect and in this way, increase in size. Highest tensile stresses acting in the zone with cracks are perpendicular to the tank axis, hence the cracks propagate in the direction of this axis. Crack growth has stopped at the boundary of the zone with separated carbides because crack tips have entered the material of higher plasticity. Crack growth conditions are already present in the thickness direction. With the increased number of broken metal ‘bridges’, acting stresses also increase, leading to a greater number of transient cracks and intensified leakage.

Based on the above, it is concluded that detected cracks jeopardise the safety of the tank. The only way to repair it is to completely remove the damaged zone. Thus, the flange is cut, along with the welded joint connecting it to the manhole opening mantle. After cutting off the zone with separated carbides and machining the groove edge, this flange is welded to the mantle again, but this time a welding technology that prevented intense heating of the austenitic material in the flange is used.

It is clear that in this case the welding technology qualification could not have been performed due to the lack of material that would match the material used for the flange. Thus the flange is welded using the technology provided by the tank manufacturer in the Collection of documents with certain corrections. The welding procedure, type of additional material and geometry of the groove are adopted based on the welding technology provided by the manufacturer, whereas preheating and interpass temperature, additional material diameter and the distribution of individual passes are determined separately.

After welding and internal water pressure testing, the welded joint is once again tested using penetrants and ultrasonic testing, and no defects are detected.

Crack in a welded joint

Figure 3 shows the imprint of a crack detected during the exploitation testing of a tank, /11/. A surface replica is obtained using black magnetic powder.

Figure 3. Crack surface replica of the weld metal.

The tank is cylindrical, vertical, heat isolated, with a diameter of 2600 mm, total height of 12000 mm, volume of 50 m^3 and is used for storing liquid carbon-dioxide. The tank is made of fine-grain steel St 52-3 N. The maximal working pressure in the tank is 16 bar, test pressure is 20.8 bar and the lowest working temperature is –40°C. The tank is a Class II pressure vessel according to standard JUS M.E2.151.

Exploitation test programme for the tank required testing all of its welded joints using magnets and ultrasound, both before and after internal water pressure tests. The crack is detected by magnetic tests before the pressure test. It is detected at the middle of the weld metal of a longitudinal welded joint in the tank mantle near the location of a circular weld, Fig. 4. Crack length is 42 mm. The reasons for crack initiation are not determined.

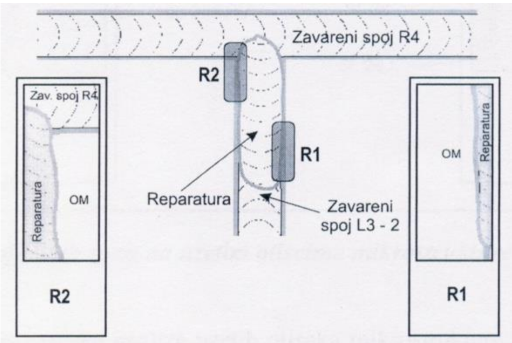

Figure 4. Location of crack repair.

The crack is removed by grinding. At the same time, magnetic tests are performed. The crack is removed after grinding to the depth for the remaining wall thickness of 9 mm. Since the minimal analytical wall thickness for this tank is 9.5 mm, and the tank owner did not want to reduce the maximal working pressure in the tank, and the wall thickness needed to be restored to its initial value. It is achieved by surfacing the repaired location in accordance with the technology prescribed for such situations.

Performing surfacing with this technology is characterised by following conditions: relative high carbon content, required high surface layer quality (B according to SRPS ISO 5817), welding in an inadequate position and impeded surface layer contraction. Taking into account that surfacing is supposed to be done inside the tank at the height of 8 m, on a relatively small surface, the MMAW procedure is selected. Conditions, such as high carbon percentage in the parent material (max. 0.20%), welding in a vertical position (only possible with smaller electrode diameters and weaker current, which results in lower energy input and quicker cooling), working at heights in the open (occasionally causes accelerated cooling due to draft) and cooling of the welded joint in limited (impeded) contraction (which results in significant residual stresses), all contributes to the occurrence of hard and brittle structures and high residual stresses, which results in cold cracks. For the purpose of preventing this, the preheating and interpass temperatures are increased by around 20% relative to those obtained analytically and are carefully maintained during surfacing. Further slowing of cooling and the reduction of residual stresses is achieved by controlled cooling of the welded joint during surfacing.

The repaired location is tested using magnets and ultrasound, both on the inner and outer sides of the tank. Since no defects are detected, the tank is subjected to pressure tests. After pressure testing, the repaired location is again tested using magnets and ultrasound, and in addition, the microstructures are tested by using the replica method and the hardness is measured by using the portable Vickers method. Tests determined that the parent material has a homogeneous, fine-grain ferrite pearlite structure, and its hardness ranges from 160 to 176 HV. No defects are detected in HAZ. HAZ microstructure consists of bainite with traces of martensite and hardness ranging from 198 to 208 HV. The weld metal structure consists of proeutectoid ferrite and upper bainite with hardness ranging from 176 to 180 HV.

Test results are evaluated as satisfying and the tank is put into further exploitation. The repaired location is denoted as mandatory for testing during the next exploitation test of the tank.

Crack in the fusion line

Figure 5 shows the cross-section through a welded joint of a tank in which a crack in the fusion line is detected during exploitation tests, /2/.

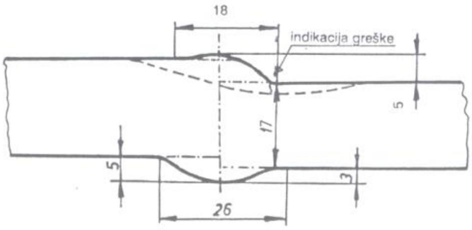

Figure 5. Cross-section of welded joint at the crack location.

The tank is cylindrical, horizontal, heat isolated, with a diameter of 3000 mm, length of 7900 mm, volume of 50 m^3 and is used for storing liquid carbon-dioxide. The tank is made of microalloyed steel P460NL1 (NIOVAL 47). Maximal working pressure in the tank is 20 bar, test pressure is 26 bar, and the lowest working temperature is –50°C. The tank is a Class II pressure vessel (according to standard JUS M.E2.151.

The exploitation test programme for the tank required magnetic and ultrasonic testing all its welded joints, both before and after internal water pressure tests. The crack is detected by magnetic tests before the pressure test on the fusion line of the circular welded joint between two mantle segments. The crack had a length of 60 mm and a depth of 3 mm. Exact position of the crack (fine-grain or coarse-grain HAZ) could not be determined. The reasons for crack initiation are not determined.

In order to determine whether the crack should be removed or not, the procedure for failure risk evaluation, defined in regulation PD 6493, /9/, should be applied. In order to apply this procedure, strength and plastic properties should be known, along with the stress state in the zone containing the crack tip, and the zones through which the crack tip will propagate during its growth. Data on strength and plastic properties of HAZ is taken from literature, /12/. This data is obtained by testing specimens of steel P460NL1 subjected to a simulated welding thermal cycle. Evaluation is performed for two zones within the HAZ, the one with the lowest, and for the one with the highest strength and toughness. The performed procedure shows that in case the crack tip is located in the first zone, there is no risk of failure, and in the case the crack tip is located in the second zone, there is a risk of failure. Aforementioned analysis had taken into account only stresses caused by test pressure and residual stresses. A degree of uncertainty is present in this analysis due to the fact that the values of stresses caused by change of shape due to the welded joint overlap and misalignment, and thermal stresses that occur during the cooling of the vessel at start up.

Crack shown in Fig. 5 will continue to grow perpendicularly to the sheet surface due to highest stresses. It is known from literature, /2/, that residual tensile stresses are highest on the surface and they spread up to 20% of wall thickness. This means that, during crack growth, its tip will reach the area of reduced residual stresses. Taking into account that the considered welded joint is welded as an X groove, the crack will, during its growth, pass through HAZ and reach the fine-grain structure of the parent metal, with significantly higher toughness. If the crack tip starts to follow the fusion plane, then the angles of crack propagation and the direction of principal stresses are reduced, which also reduces the acting stresses. In this way, crack growth could stop at a certain depth, due to an increase in material toughness. Favourable conditions for crack growth remain in the lateral direction i.e. along the fusion line. Due to this, the possibility of repairing this crack is considered.

Taking into account that the maximum crack depth is 3 mm, it can be expected that, after the crack is removed by grinding, the remaining wall thickness at this location will be 14 mm. Stress in the tank wall, in the circumferential direction, at test pressure and for thickness of 14 mm will be 279 MPa, which is below material yield stress (the plate containing the crack has a yield stress of 584 MPa), /2/. Based on the above, it is concluded that the crack can be repaired by grinding. In order to avoid stress concentration, the repair location is made in spherical form with a slight transition from thinner to thicker cross-section, shown by the dotted line in Fig. 8. Magnetic tests are performed alternatively with grinding. The crack is removed after grinding to the point where the remaining wall thickness is 14 mm.

The repair location is tested using magnets and ultrasound at both inner and outer sides of the tank. Since no cracks are detected, the tank is subjected to pressure tests. After the pressure tests, the repair location is again tested by magnets and ultrasound, and no cracks are detected. Test results are evaluated as satisfying and the tank is put into further service. The repair location is denoted as a mandatory location for future exploitation tests of the tank.

CONCLUSIONS

Documents and reports of exploitation tests represent the basis for reliable determining of the current state of pressure equipment.

Pressure equipment safety can be increased by testing locations where cracks are most likely to occur and by increasing the scope of non-destructive test methods and their sensitivity.

The scope of non-destructive test methods should be increased with the increase of crack initiation probability and reduced availability of documentation.

Unacceptable defects that occur during manufacture are frequently detected during exploitation tests. In the case that no cracks occur, these defects do not need to be removed, since there is a possibility of damaging the defect location due to poor welding conditions, introduction of additional internal stresses and grinding.

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