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Damage Analysis of Dissimilar Metal Welds of Power Equipment

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Abstract. Heterogeneous dissimilar welds (DMW) are always problematic and critical areas of pressure vessels and piping. A critical structural area is created by combining two materials with different chemical composition and with completely different mechanical and physical properties, especially different thermal expansion. This critical detail very often undergoes intensive degradation during operation and very often, the operational degradation of the junction of the two materials with different properties ends with the loss of integrity of the pressure boundary. There are three main factors leading to failures – higher operation temperature than design parameters, inappropriate design of a heterogeneous welded joint to areas with higher stress levels and poor erection quality, where defects are already in the welded joint from assembly. The cause of the failures is also other factors that are not known at the design stage of the pressure units or are not sufficiently evaluated. Susceptibility to stress corrosion cracking (SCC) of one of the used DMW materials during long time operation is one such unknown factor in the design stage. Stress corrosion cracking is the growth of crack formation in a corrosive environment. It can lead to unexpected sudden failure of normally ductile metals subjected to a tensile stress. The stresses can resulted from the crevice loads due to stress concentration, or can be caused by the type of assembly or residual stresses from fabrication.

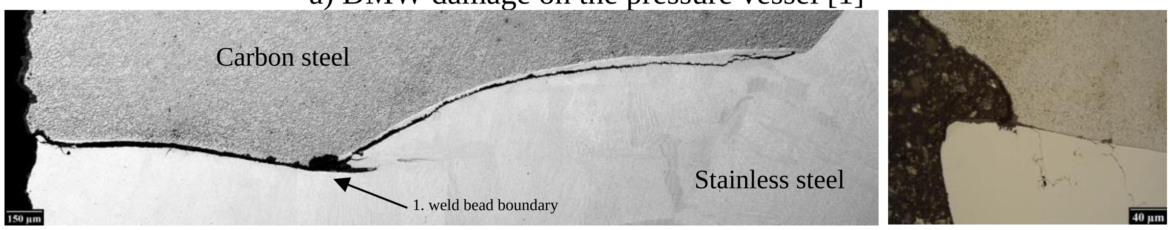
Introduction

It is common practice in the power industry to produce robust pressure vessels from carbon steel and connecting piping systems from austenitic steel. A critical structural detail is created by combining two materials with different chemical composition and with completely different mechanical and physical properties, especially different thermal expansion. This critical detail very often undergoes intensive degradation during operation and very often, the operational degradation of the junction of the two materials with different properties ends with the loss of integrity of the pressure boundary. The cause of the damage is usually a number of factors that are not known at the design stage of the pressure units or are not sufficiently evaluated.

Description of Dissimilar Metal Welds (DMW) Damage

The two materials with different material properties connection is done in the power industry by welding. Welding of materials with different structural phases leads to degradation of the weld joint in heat-affected zone already within manufacturing. During welding and subsequent heat treatment at temperatures above 600 ° C, significant diffusion processes occur between the base material and the weld metal, mainly when a filler material is not stabilized. Carbon diffusion from a carbon steel (0,2C-1,0Mn-0,3Cr-0,3Ni) to austenitic filler material (0,08C-15Cr-25Ni-5Mo) results in the formation of decarburized and the carburized zone in the melting area and formation of carbides, which usually segregate at grain boundaries. This, together with the action of the media process and especially the high level of stress due to the very different thermal expansion of the carbon and austenitic steels during operation condition, leads to a significant reduction in the reliability, durability and safety of the weld joint as can be seen in Fig.1. Manufacturing process of the DMW joints so created the conditions for crack propagation along the fusion line of the first buttering layer.

a) DMW damage on the pressure vessel [1]



b) DMW damage on the piping system [2, 3]

Fig. 1: Damage of DMW along diffusion line

Initial Phase of DMW Degradation. It can be seen from presented figures 1 that DMW damage always start from corrosion defect on the inner surface, where the corrosion sensitive parts of weld joint has been (revealed) in a contact with the working medium. Corrosion of this part can produce pitting which can be significant as stress concentrator. The concentrator on the inner surface, additionally significantly increases the stress gradient from the different thermal expansion of the carbon and austenitic steels that is approximately 33%. Typically, a failure of DMWs usually occurs during heating startup operation condition and not during normal operation condition. The stress gradient during heating due to different thermal expansion of used materials increases extremely at a corrosion defect tip. Conditions are created for the second part of the failure. The stress level at a corrosion defect tip is dependent on the geometry of the formed stress concentrator.

The different thermal expansion of the used materials also damages the high temperature protective oxide layer during cooling. This high temperature oxide is formed on the inner surface during long-term operation of the pressure equipment at higher temperatures [5]. The metal is exposed by damaging the passivation layer and the exposed bare steel surface is immediately oxidized by increased velocity. The passivation layer damage due to the different expansion of the materials increases the corrosion rate of the inner surface damage. Accelerated corrosion damage creates a higher stress concentrator sooner than operation lifetime and it creates the conditions for the second phase of damage - the crack propagation from the corrosion defect. Damage time of DMW depends on the time of creation of the suitable stress concentrator.

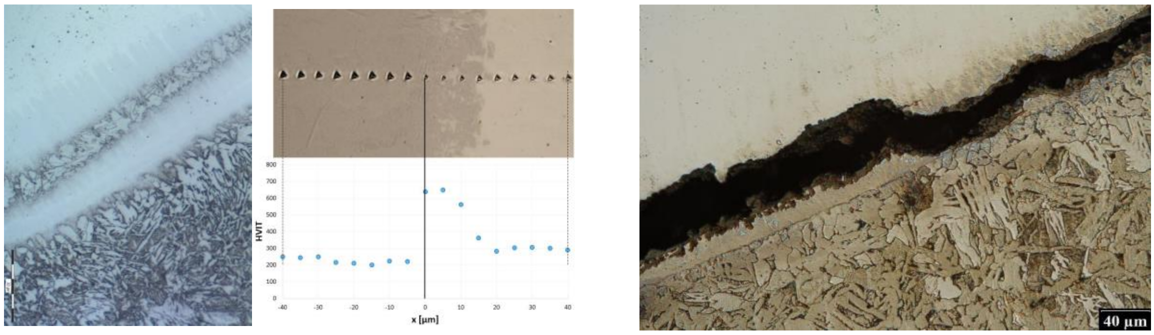


Fig. 2 Path for stress corrosion cracking degradation [4]

Phase of Crack Propagation by DMW. A very high hardness region was found by measuring the micro hardness across the weld joint (Fig.2).. During the manufacturing welding of used materials with different chemical composition and subsequent post weld heat treatment, a narrow path of material with a very high hardness is formed on the boundary of the diffusion layer at a depth of about 50 micrometers from a significant fusion line. Measured hardness up to 750 $HV_{0,01}$ (Fig. 2) indicates a very hard and brittle material without significant plasticity. There are three materials with completely different plastic behaviour in this DMW type - carbon decarburized material, narrow area with created carbides with very high hardness and austenitic plastic material. The damage always occurs in a region, which is most susceptible to cracking. When the corrosion damage on the inner surface connects with this narrow path at the diffusion boundary, conditions for initiation and subsequent crack propagation from this corrosion defect are created. Practice shows that DMWs are damaged only during transients. As soon as the tension due to the change of temperature and different thermal expansion of the used materials reaches the fracture stress of the narrow path, initiation and fast crack propagation occur through this path. Initially, the crack driving force is extremely high due to the stress concentrator, therefore the material is also damaged perpendicularly to the main crack where carbides on the grains boundaries are located. Crack growth is realized by stress corrosion cracking. Stress relaxation occurs during crack propagation and because stress relaxation is faster than the temperature change during the heating (or cooling) of pressure vessels to operation temperature, the crack arrests on the any material barrier, which is usually the subsequent weld bead. The narrow path with very high hardness is not continuous along the fusion line, which is another reason for the crack arresting. After crack is stopped and the second weld joint damage phase is terminated, the initial damage phase begins again as written above [6].

Corrective Measures

The main principle in design of welded structures in the case of DMW has to be kept. Location of a welded joint in places with lower stress areas should be designed. However, the different thermal expansion of the used materials reduces the importance of this essential requirement. Therefore, further corrective measures must be taken.

Post Weld Heat Treatment (PWHT). Post weld heat treatment on residual stress removal in the manufacture procedure of welded components is commonly designed and implemented. Especially when welding two pieces with a larger wall thickness over 20mm, where an austenitic buttering is welded onto the base carbon steel. In the case of DMW, the PWHT is not entirely optimal. Compressive residual stress is in heat-effected zone (HAZ) of DMW before

PWHT application and residual stress should be minimal after PWHT applying. But in case of DMW it is just on opposite. PWHT is usually conducted at 620-640°C. The structure is heated to this temperature and is kept several hours at this temperature. Residual stress is minimal or neglected at the end of dwell. But very high residual tensile stress is created in HAZ during cooling from PWHT temperature to room temperature due to different thermal expansion of austenite and carbon steel. Compression barrier against cracking is replaced by very high tensile residual stress. This effect of PWHT is very negative in case of structures with DMWs. It is recommended to not perform PWHT on DMW.

Humidity. Very high humidity increases metal corrosion rate mainly when the humidity is over 50% after drainage of pressure equipment. The high humidity inside the pressure equipment during long-term shutdowns or outages is very negative if the passivation protective layer of the created oxides is destroyed during cooling in DMW areas. High humidity increases the speed of the stress concentrators creations and thus accelerates the initial phase of the DMW degradation. It is recommended to keep the humidity inside pressure equipment under 50% during shutdowns or outages when drainage was done.

Oxygen. Very often, the pressure equipment is not drained during shutdown and the boiler water remains inside pressure vessels. The oxygen content of the boiler water during operation is very carefully monitored. However, during the shutdown, the oxygen content of the water is not controlled and it is completely ignored. The presence of oxygen in the water during two months shutdown significantly increases the corrosion attack of DMW materials, especially when the DMW passivation layer is broken after cooling. The oxygen saturation in water greatly accelerates the formation of stress concentrators in the DMW area and thus decreases the failure time by the crack propagation in filler material of DMW. It is recommended to control the oxygen content of the water during cooling and outages.

New Filler Material. Non-stabilized filler material with higher content of nickel (25%) and low content of chromium (15%) was used in our case. Used filler material also had a relatively high phosphorus and sulfur content, leading to increased weakening of the grain boundaries in HAZ after welding. In addition, during the welding, chromium reacted with carbon from the base material. Carbides together with the higher content of sulfur and phosphorus created areas on diffusion border with very hard quenched structures. All these led to the replacement of the filler material. Practice and experimental analysis showed that filler material with higher chromium content (25%) and lower nickel content (12%) is better suited for use as a transition wire. However, the replacement of the filler wire does not fully solve the root weld area susceptible to corrosion attack.

Protective Layers. As it was mentioned above, the replacement of currently used filler wire will not completely eliminate DMW problems. Even a change of DMW welding technology does not lead to the suppression of unwanted very hard structures. The only way to prevent stress concentrators (corrosion damage of the surfaces) in the DMW root area is to completely separate the material sensitive to stress corrosion cracking from the operation medium. It can be achieved in several ways: a) by welding anti-corrosion layers to the inner surfaces; b) galvanic nickel-plating of inner surfaces; (c) hot or cold sprays application on surfaces. Each of these methods has some advantages and disadvantages. From all mentioned methods, the method of galvanic depositing of the nickel layer on the inner surface was chosen and experimentally tested. Specimens of weld joints with nickel deposit were tested in air and in corrosion environment. The nickel protective layer of DMW appears stable even in cyclic temperature changes after solving the problem of adhesion of the nickel layer to the austenitic material. This method is currently applied on the sites.

Conclusion

The time of the power equipment operation has shown that the DMW with buttering layer is sensitive on intercrystalline corrosion and stress corrosion cracking. DMW with this buttering layer is one of the most critical areas of pressure equipment. DMW damage limits the lifetime of the power equipment, so regular attention must be given to these areas during the operation. One of the first tasks was to find all DMWs of this type and to include these DMWs in a regular operational inspection program. Volume NDT inspection had to be qualified along with their inclusion in the surveillance program since the appearance of weld joint heterogeneities makes detection of defects in the weld joint very difficult. An evaluation method of detected flaws in DMW had to be also developed. The newly developed evaluation method determines the acceptability of the defects and critical defect size in DMW. The critical size value determines the time until the DMW repair as well as the NDT inspection interval. New DMW repair technologies in dependence on the diameter and wall thickness of the repaired equipment had to be also developed due to the findings of defects in DMW. Fully automated welding equipment increasing DMW quality has been introduced. All of these activities have been aimed at maintaining the operability and reliability of power equipment.

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