Case Study on Failure of Ti Lining

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Abstract: Process equipment as well as their components are subjected to various damage mechanisms resulting from operating conditions, material ageing, upset conditions, environmental factors as well as neighborhood driven events. The absence of adequate inspection, repair and maintenance strategies can aggravate material problems causing pre-mature failures. This article addresses the failure incident of a newly applied Ti lining on the flange of a pressure vessel that rendered the whole process unit to outage. Further, it addresses the various factors that can be critical to the lining repairs considering various physical, metallurgical and electrochemical facets. Finally, it addresses the importance of conventional mock-up techniques towards mitigation of failure risks.

Key words: Ti lining, welding distortions, ductile fracture, mock-up repair.

1. Introduction

Hydrocarbon industries spend significantly large amounts on maintenance programs due to material failures resulting from corrosion as well as other mechanical damages. It has been reported that industrialized economies lose 5% of their revenues in asset damages resulting from corrosion [1]. The maintenance related expenditure can be even more if we take into considerations material failures resulting from damages other than corrosions [2]. On the other hand, there have been consistent efforts in combating corrosion and degradation of materials. Since last decade, there has been an advent in addressing uncertainties associated with degradation behavior of materials; where RBI (risk-based inspections) and FFS (fitness for service assessment) have minimized the ambiguities thereby helping towards understanding as well as mitigation of certain material damages [3]-[5].

On the other side, there are certain scenarios where the applicability of above said techniques (RBI, FFS etc.) is not viable or can't effectively address certain uncertainties. Moreover, the acquisition of real representative data and subsequent analysis of collected data (especially from aged equipments) is a concern that subsequently limits the applicability of simulation software(s) and other detailed analyses tools.

As of today, many pro-active and reactive approaches to combat material damage mechanisms have been proposed in consultation with standard recommended practices, case studies, in-house lessons learnt database and expert judgment etc. In the presence of all these information and subsequent actions from these recommendations, there is still a room for material deterioration; that can be attributed to lack of judgment, in-effectiveness of collected data and perhaps some unknown factors. In the event of uncertain behavior of aged materials (during welding repairs), the use of conventional mockup repair (in addition to those generally meant for craft personnel's qualifications) prior to repair can reveal and address the risks.

2. Case History

A vertically oriented pressure vessel meant to contain high temperature hydrocarbon product suffered leakage from the top-side flange (upstream portion). The vessel's shell was constructed from CS (carbon steel) A516 Gr. 70 (UNS K02700) and flange was made from CS A105 (UNS K03504). Internal portion of pressure vessel and flange's face were lined with Titanium grade-2 (UNS # R50400) to avoid exposure of underlying CS with operating conditions of hydrocarbon stream. On the other hand, there was high risk due to high fluid inventory of this pressure vessel pertaining to its larger dimensions (diameter: 2.5 mtr., height: 10 mtr.), high operating pressure and high flow rate [4]. Considering the severity of hydrocarbon stream, the whole process unit was subjected to emergency outage in order to perform the necessary repair works on the flange.

The flange bolts were removed, followed by dismantling, lifting of top cover (using crane) and gasket removal in order to investigate the reasons behind flange leak. Visual, ultrasonic and liquid penetrant inspections revealed thinning as well as punctures, at the various portions of Ti lining on the flange's face that resulted in leaks from flange's face.

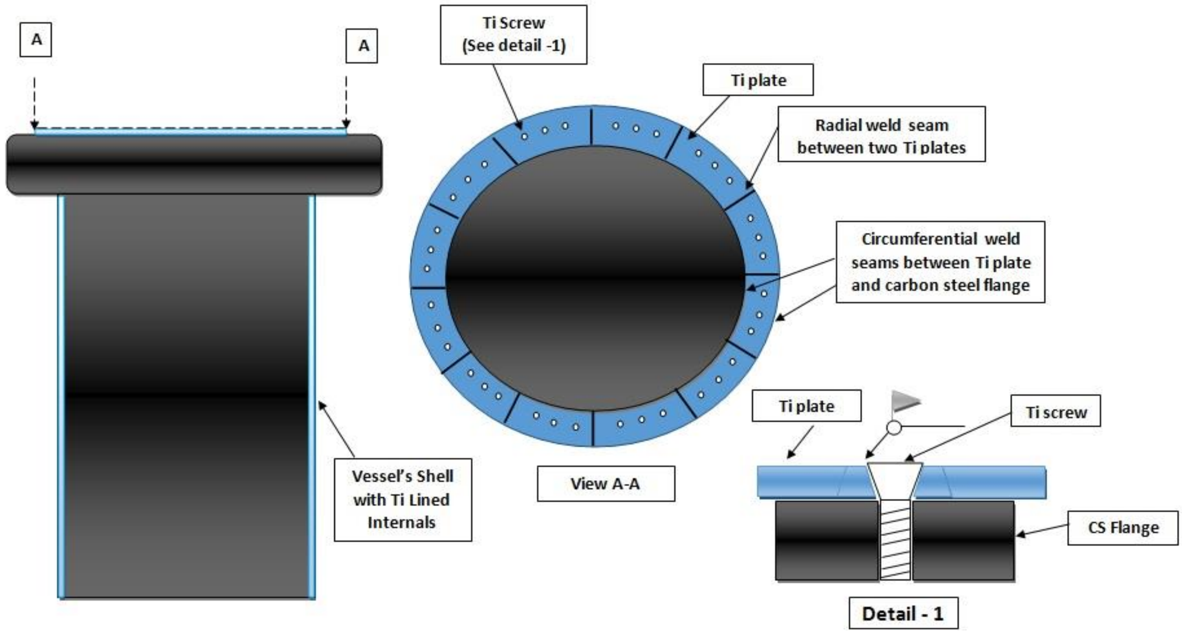

Fig. 1. Proposed arrangement for Ti lining and bolts on flange's face.

The damaged lining on the flange's face was removed by grinding to access the underlying carbon steel surface. Grinding and in-situ machining were performed to clean and smoothen the surface of carbon steel. In order to aid the reinforcement of new Ti lining (3 mm thick Ti plate) on CS surface, and to minimize the weld distortions; a design was proposed that included the tapped grooves in CS flange and three numbers of through-holes (tapered) in each Ti lining segment. Fig. 1 shows the proposed arrangement of Ti lining, radial weld seam and Ti bolts. Ti lining were supposed to be reinforced to CS flange using Ti bolts that will pass through the holes and meant to be tightened in the tapped grooves. Grooves were made on the surface of carbon steel flange as per proposed design. Exposed surface was checked by dial indicators to observe any distortion as well as mis-leveling on the flange's face. Ti lining segments (i.e. 3 mm thick plates) were placed on the face of flange followed by fit-up (using tack weld) and hand tightening of Ti bolts to fix the lining onto flange's face. Welding of Ti lining (the radial and circumferential weld seams) with flange's face was performed using GTAW (gas tungsten arc welding) in line with applicable WPS (welding procedure specifications). After welding of Ti lining with CS surface, Ti bolts were fully tightened (using screw drivers) to force the lining sit in a flat manner. Projected portion of Ti bolts (i.e. leftover projections after tightening) beyond Ti lining's surface were welded with surrounding Ti lining, followed by flush grinding and liquid penetrant examination.

In-situ machining was performed on the Ti lining to level-off the surface and remove any weld reinforcements (for circumferential and radial weld seams), Ti bolts, and distorted lining from heat of welding process. Liquid penetrant examination was performed to check any cracks or surface defects that incurred during welding and in-situ machining. Moreover, the surface distortions were checked using dial indicators to ensure the leveling and smoothness of in-situ machined surface. The flange's face was declared as acceptable for use in the intended hydrocarbon service, and the box up was performed by installing the top cover along with new gasket between the mating faces of flange and top cover.

The pressure vessel was filled with water for subsequent pressurization up to the intended hydrostatic test pressure. Right after filling of vessel (and before pressurization), severe leakage was observed from the flange's face. All flange bolts were re-checked for tightness, but the leakage seemed to be from newly installed Ti lining. Therefore, it was decided to re-inspect the leaking portion of flange's face. Water was drained from the vessel followed by dismantling of dish head. Visual inspections revealed that Ti lining had failed-off at multiple locations around the circumference of the flange due to thinning and punctures. Also, some localized voids were observed that indicate delamination between the Ti lining and CS flange surface. The failure of Ti lining delayed the repair leading to prolonged downtime incurring subsequent maintenance challenges.

3. Results and Discussion

Post-failure visual analyses revealed that Ti lining had bulged and fractured at multiple locations around the circumference of flange's face. Also, ultrasonic examination revealed thinning of Ti lining with resulting thickness up to 0.5 mm (instead of ~ 3.0 mm) in the vicinity of fractured Ti lining. Damaged Ti lining was peeled at thinned locations (using grinding) in order to inspect the cross-section of interface between lining and flange's face. Considerable voids between thinned Ti lining and underlying CS flange were observed; and were indicative of lining delamination due to bulging. Here, thinning of certain segments of Ti (relative to others) can be attributed to non-homogenous gap between Ti lining and CS flange, as lining wasn't perfectly sitting (rather distorted) on the underlying CS flange. Ti lining was bulged even before the in-situ machining due to higher heat intake from continuous welding and absence of any distortion control strategy. It is worth noting that lining distortion due to welding heat is a dislocation movement mechanism; that follows the pattern of caterpillar movement from hot end of plate to the colder end [1].

The same gap i.e. between Ti lining and underlying CS flange led to un-even surface of Ti lining, thereby leading to non-homogenous material removal during in-situ machining. Moreover, the absence of leveling checks (by dial indicators) before in-situ machining (and after welding) resulted in unrevealed and bulged (rather even) face of Ti lining. Due to this un-rectified bulging of Ti lining's surface, in situ machining caused more removal of material from the portions that were bulged compared to the rest of/ un-distorted lining. Fracture failure happened at the same portions that were subjected to thinning from bulging and subsequent machining as shown in Fig. 2. The fractured edges of Ti lining showed some localized elongation, that's an evidence of ductile fracture under the load of top cover at the portions with reduced thickness.

Here, consideration of dislocation motion and consolidating the bolts tightening sequence with weld heat control, and movement of welding torch could have minimized the lining distortion. Repair strategies should take into consideration relative coefficients of thermal expansion of dissimilar metals as it is critical to the formation of voids between lining and underlying material. An example would be the use of SS (stainless-steel) lining on carbon steel's surface, where higher relative thermal expansion coefficients (of CS & SS) may cause the formation of voids. The possible alternative solutions in such scenarios could be welding build up using SS electrodes or use of factory-applied SS claddings on CS. Another known practice is to limit the use of such material combinations (that are prone to voids from differential expansions) to the applications not mandating leak-tight joints.

Standard guideline suggests that the internal linings in pressure equipment are prone to failure at weld seams due to combined impact of stresses and corrosion, a phenomenon known as stress corrosion cracking [5]. In the event of lining failures, the corrosive service seeps into the space between lining and underlying metal. The extent of damage to underlying metal remains unpredicted and is driven by numerous factors such as corrosivity of service to underlying metal, the amount of seeped service, travel distance of seeped service under the lining etc. Such instance (unless taken care with appropriate NDE program) can trigger the accelerated corrosion of base metal leading to catastrophic failures.

Another aspect to be considered is the geometry (i.e. orientation) of claddings. It has been reported that the pits/ groves formation is impacted by the gravity [1]. Also, Rana *et al*. has reported the formation of shallow and wide pits on the shell courses of storage tanks from corrosive water. On the other hand, deep and narrow pits were observed on the bottom segment due to the added impact of gravity [6]. Hence the lining failures at any bottom segment can lead to relatively accelerated failure of equipments (than side-ways segments) under the combined effect of corrosion, stresses as well as gravity. In certain instances, the underlying metal thickness is high enough mandating the stress relieving after the welding of linings with underlying metal. In the event of inadequate heat treatment (or excessive temperatures for longer durations) there is likely sigma phase embrittlement in austenitic and duplex SS linings, that can lead to premature failure of these linings [2].

Hence, the condition (corrosion resistance, smoothness etc.) alongwith thickness and geometry of underlying metal, the intended cladding-material combination, heat treatment etc. are the factors that can dictate the long-term integrity of internally lined pressure equipment. The mock-up repairs involving welding, assembly etc. can identify the roadblocks with any proposed repair procedure. Finally, relative positions of lining metal and underlying metal in galvanic series is also crucial along with service conditions as this factor governs the possibility of galvanic corrosion [2].

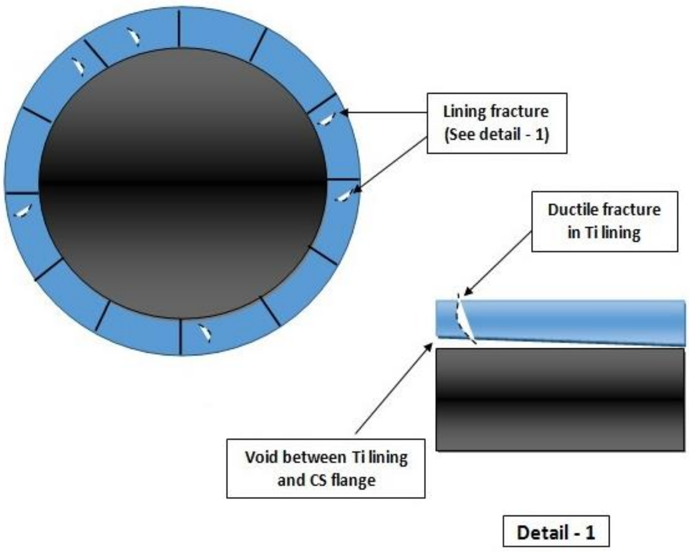

Fig. 2. Damaged lining on flange's face due to thinning and voids.

4. Conclusions

The following conclusions can be drawn from the concurrent analyses of failure incident, metallurgical constraints and applicable options:

Consideration of metallurgical mechanisms (such as dislocation movement due to weld's heat) can be vital in developing the applicable welding and distortion control procedures. Dial indicator test after welding of lining (and before machining) is highly crucial and can reveal distortions and can aid in pro-active addressing of any thinning from in-situ machining. Thickness and material of cladding/lining plates should be as to compensate for machining allowance as well as to withstand compressive loads in ductile fashion in the event of any gaps/ distortions. Always conduct point contact test (e.g. blue match paste test) between lining and underlying material before fit-up in order to reveal any mismatch among the mating surfaces. Furthermore, a well-established mockup strategy for repair of aged and dissimilar materials can reveal bottlenecks and constraints that are likely to occur during actual repair works. Finally, the repair strategy for any damaged lining should take into consideration various factor such as galvanic numbers of dissimilar materials, sensitivity of surface's flatness towards leak tight application, geometry, level of ductility for lining, relative coefficients of thermal expansions for lining and underlying metal as well as condition of underlying metal etc.

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