Failure investigations of failed valve plug SS410 steel due to cracking

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Abstract. Premature and sudden in service failure of a valve plug due to crack formation, applied in power plant has been investigated. The plug was tempered and heat treated, the crack was originated at centre, developed along the axis and propagates radially towards outer surface of plug. The expected life of the component is 10-15 years while, the component had failed just after the installation that is, within 3 months of its service. No corrosion products were observed on the crack interface and on the failed surface; hence, causes of corrosion failure are neglected. This plug of level separator control valve, is welded to the stem by means of plasma-transferred arc welding and as there is no crack observed at the welding zone, the failure due to welding residual stresses are also neglected. The failed component discloses exposed surface of a crack interface that originated from centre and propagates radially. The microstructural observation, hardness testing, and visual observation are carried out of the specimen prepared from the failed section and base portion. The microstructure from the cracked interface showed severe carbide formation along the grain boundaries. From the microstructural analysis of the failed sample, it is observed that there is a formation of acicular carbides along the grain boundaries due to improper tempering heat treatment.

1. Introduction
Failure of mechanical components is an unpreventable issue in power, chemical, refinery and nuclear industries due to severe working conditions such as high-pressure steam, corrosion, fatigue, wear and abrasion etc. The components of control valve, turbine, boiler and pump such as, stem, pipes, shafts, gears, impellers, tubes, flanges, couplings etc. fails regularly during the operation. During ongoing operation, a shutdown for fixing these damages costs a lot; it is venerable to carry out prior inspections on the handy units to avoid this kind of failure. In general, power industries involve very large industrial complexes containing various units. The common causes of the failure of mechanical components used in power, chemical, refinery and nuclear industries are investigated earlier by researchers that are, stress corrosion cracking, welding failure due to fatigue, pitting corrosion, residual stresses, improper heat treatment of components etc. Delavar et al. [1] investigated the causes of cracking of stainless steel flange used in petroleum refining and the petrochemical operations. It was investigated that the failures occurred due to stress corrosion cracking caused by the presence of chloride in the anti-seize grease due to high temperatures and high-pressure condition. Roy et al. [2] investigated the in-service failure of an economizer tube and it was observed that, a localised corrosion directed towards the failure of economiser tubes forming corrosive products and cracks. Suess et al. [3] carried out the investigation of in-service cracking of turbine inlet block made up of 410 stainless steel.
the investigations was carried out with scanning electron microscope (SEM) and it was revealed that, the crack was developed due to formation of grain boundary carbides and these carbides likely formed during tempering of the part. Schroeder [4] investigated the metallurgical failure analysis of a fractured steam control valve stem made up of Incoloy 901 alloy. SEM with energy dispersive x-ray spectroscopy, tensile testing, hardness testing, chemical analysis and metallographic analysis was carried out to trace the exact reason of failure. Jung et al. [5] carried out the metallographic analysis of the specimen prepared from failed stem of isolation valve used in nuclear power plant. The identified causes of failure was precipitation of non-metallic inclusions with higher hardness at the failed region, this was due to improper tempering process applied to stem. Parnian [6] carried out the failure investigations of austenitic stainless steel tubes used in a gas fired steam heater. The cracks developed on the tube were examined and hardness was measured at the seam weld, heat affected zone and U-bend areas. Microstructure investigations were carried out with optical microscopy and SEM and it was revealed that the cause of cracking was stress corrosion. Das et al. [7] investigated the premature failure of the impeller blade of coke plant, which reveals exposed surface of a crack. The microstructural observation at weld zone was carried out and it showed severe intergranular corrosion, which causes the failure. Shirinzadeh-Dastgiri [8] had carried out the failure investigations of failed weld joint in AISI 1518 low carbon steel pipeline with the help of non-destructive testing, radiographic and metallographic analysis. The identified causes of failure was improper welding since, micro-cracks were noticed on the weld interface and possible corrosion attack due to cracking, this corrosion mechanism was studied by electrochemical techniques. Sharma and Roy [9] investigated the failure of AISI stainless steel pointer rod, visual inspections, microstructural investigations with optical and SEM were carried out. It was investigated that, the presence of MnS inclusions and deformation-induced martensite affected the pitting corrosion resistance causes the failure of pointer rod. Qayyum et al. [10] carried out numerical simulation of cracked disc of AISI H-11 tool steel, results showed significant drop in hoop stress with increase in number of cracks, thus limiting the number of cracks possible in a thermal fatigue crack network. Tsai et al. [11] studied the phase transformation phenomenon in AISI 410 steels that will helped in determining the causes of failure. Raghu Shant et al. [12] carried out the failure analysis of cracks formed at extrados of bend pipe. Recently Ma et al. [13] had carried out the failure investigations of circulating water pump of duplex stainless steel of 1000 MW ultra-supercritical thermal power unit.

As, remaining life assessment (RLA) of aged components in petrochemical in power industry becoming very important for economy and safety reasons [2]. Root cause analysis need to undertake to investigate the failure of a mechanical components to avoid such future failures. This paper describes a case history of the failure investigation of damage valve plug used in separator valve of steam power plant.

2. Case history

Control valves are the main mechanical components used to control the flow of fluid, specified volume of the flow to a specified pressure level. The basic components of the valve are stem, plug, the bearing housing and the casing. For the proper controlling of the valve, all parts must remain in the proper functioning and working condition in order to insure safe working. A premature failure of valve plug used in separator level control valve connected to steam blowing pipes due to cracking was reported on 22nd Sep 2015. Before in service, the plug was tempered and heat-treated as per requirement of the user and application. The component operated for the opening of steam flow at a pressure of 16.58 Mpa and the temperature of steam about 450-550⁰C. The expected life of the component is 10-15 years while, the component had failed just after the installation that is, within the 3 months of its service. The details site images of crack generation and failure is as shown in Figure 1. After reviewing the damaged trim pictures of failed valve from site location, it was anticipated that this could be due to delayed thermal cracking which may be due to heat treatment process tempering temperature cycles and its associated soaking time. Material for plug (SS410) is a heat-treated and is a subcontracted activity, where as per the approved procedure these activities are being carried out.
From the initial investigation, it was assumed that, the tempering might had been created problem in the HT process, where the quick cooling might have left some thermal stresses within the core of the material (Not on the surface) and after a period of time lying idle this plug might have released those stresses causing cracks axially. It was required to study the nature and likely cause of cracking. To investigate the exact issue of the crack, the methodology explained in next section is considered for the further investigations.

![Figure 1. Site failure of plug of separator valve](image)

3. Methodology
From the previous case studies of failure investigations in the past, it is found that the common methodology adopted by the investigator consist of, visual examination, radiographic examination, metallographic examination, energy dispersive spectroscopy and SEM etc. [1-8]. These approaches are useful to trace the exact causes of the failure. To identify the exact causes of failure, in the present study following approaches are used as a methodology, in which the evaluation of the main causes of failure can be identified, that consist of:

- Determination of material’s properties, such as yield, tensile strength, hardness and chemical composition.
- Visual analysis of crack surfaces.
- Metallurgical analysis of base material and cracked (failed) zone.

After receiving the cracked plug from the site, from visual observation it is perceived that the plug cracked along the axial direction, which was propagated from the centre and towards the radial direction as shown in Figure 2 (a) and 2 (b). For the detailed analysis, a plug is sliced at the bottom section and disc shape portion is removed which is followed by visual inspection, hardness and chemical testing on the disc portion, etc. Two square blocks from the disc were removed, one from the crack interface containing crack and one which is away from the crack interface representing the base material. The block that is removed from the crack section directly exposes the cracked surface after opening, which was automatically separated out and crack interface turn out to be open for observations. After the crack opening, no corrosion product was seen by visual inspection of the plug at crack interface; also at weld interface, no crack was observed. So the causes of failure due to corrosion and welding residual stresses are neglected for the investigations. Hardness of the failed component is measured and chemical composition is evaluated by the Atomic Emission Spectrometry technique. Microstructural observations of the failed region is also carried using optical microscope according to ASTM E 407.

![Figure 2. (a) and (b) Failed plug-showing crack](image)

3.1 Chemical composition of the part
The chemical composition at the crack interface and other location was measured on the disc shaped sliced portion. Chemical composition obtained through spectrometer is shown in Table 1. The chemical composition is found consistent throughout the slice surface which meets the specified requirement as per type of 410 stainless steel. This interface composition also matches with the composition reported by manufacturer, before the failure of component.

Table 1. Chemical composition of plug (Wt %)

| C  | Cr  | Mn  | Si  | S   | P   | Fe  |
|----|-----|-----|-----|-----|-----|-----|
| 0.1| 11.7| 0.8 | 0.6 | 0.15| 0.2 | 87  |

3.2 Hardness testing
Hardness testing was carried out at various location on disc shaped sliced portion to evaluate the change in the properties of material. It is observed that, at the cracked interface, higher hardness was reached. The measured hardness near the cracked interface was of 44-46 HRC and that of base material it was 39-42 HRC. The hardness values measured at various points on the sliced sample from the failed plug is shown in Figure 3.

![Figure 3. Hardness at various zones of sliced section](image1)

The specimen along with image view of the crack prior to and after opening is shown in Figure 4 (a) and (b). The opened crack exhibits features that indicate relatively brittle fracture. The measured hardness of the base material varies in the range of 39-42 HRC is consistent with the quenched and tempered condition of material but at cracked portion higher hardness is noticed than other locations.

![Figure 4. Block from cracked portion showing open crack](image2)

3.3 Metallographic analysis
For the metallographic study, from each sectioned block, one small cross section sample is removed. One from the cracked interface and other away from cracked to represent base material and to document the crack morphology using optical microscope.

The main crack surface shown in Figure 4 (b) shows brittle failure zone. The cracks started from the inner surface, i.e. from the centre of plug, which travels axially and propagated along the radius, towards to the outer surface. In order to observe the surface microstructure, the sectioned sample was first mechanically wet ground using a 1500 grit silicon carbide (SiC) paper, then polished with aluminium oxide (Al₂O₃) powder of 3 and 0.25 mm diameter, followed by electro etching according to ASTM E 407.
After etching, the specimen was cleaned with distilled water and methanol, and then dried in air. Subsequently, the specimen was examined with an inverted optical microscopy (OM). It was observed that the surface microstructure of the plug had a tempered martensitic structure, as shown in Figure 5.

The metallography of the cracked sample revealed highly distributed grain boundary carbides, which are both intergranular. Un-etched magnified image of cracked surface as shown in Figure 5, reveals various cracks originating from the cracked zone. Several abnormalities in the cracked interface region are observed in the microstructure. Micro cracks and cracks have been observed at several locations, mostly originating from the main crack. However, the microstructure from the base region that was unaffected shows a martensitic matrix without any irregularity, the magnified surface of base region without etchant is also shown in Figure 6 which does not show any such crack initiations or other effects.

Higher magnification study of the microstructure, as shown in Figure 7, revealed evidence of continuous grain boundary carbides which are mostly originated from the cracked surface. The distribution of heavy carbides along the grain boundaries can be revealed clearly in Figure 7.

Figure 5. Magnified image of cracked interface surface

Figure 6. Magnified image of base portion surface

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Figure 7. Microstructure of crack interface

4. Observations and Discussions
The plug used for separator level control valve was reported failed during service due to cracking. Tempering and heat treatment are the subcontracted activities were carried out on the part before installation. To carry out the failure investigations of the plug, visual inspection, chemical composition testing, hardness testing and metallographic analysis was carried out. It is observed that, the chemical composition of the part is consistent with the 410 martensitic stainless steel as per the requirement. After, the visual inspection of the cracked surface, the brittle transition nature of failure was observed. As, no corrosion products were observed on the surface of cracked interface it can be concluded that this failure did not associated with the corrosion. While, the hardness at the various location on the failed part was measured and it was observed that higher hardness was obtained at the vicinity of cracked surface than other locations. Microstructure of the cracked interface revealed heavy grain boundary carbides at the cracked interface, which are undesirable due to their brittle nature. Such carbides tend to serve as crack propagation sites, thereby significantly reducing the fracture toughness of the material. As far as the metallographic study is concerned, the carbide like structure near the grain boundaries of the cracked interface and the microhardness of the structure was higher at failed interface. That may be caused due to improper tempering of the part forming brittle failure that lacking in tensile strength resulting weaker areas along the axis and failure might occurs due to sudden impact of steam during working.

This evaluation exposed extensive indication of embrittlement at the cracked region which is due to the presence of grain boundary carbides and these carbides likely formed during tempering of the part. Based on these findings, it is recommended that the heat treating process need to be modified in order
to avoid the formation of grain boundary carbides. Generally, a range of tempering temperature in between 1,050 to 1,125 °F is recommended for 410 SS steel part to avoid carbide formation [3].

5. Conclusions

The metallographic observations and hardness measurements of the specimen prepared from the failed portion lead to the conclusion that, the heat treatment applied to the valve plug might have gone wrong and the tempering caused the failure. The microstructure showing the continuous grain boundary carbides that leads to weaken the areas for tensile strength and cracks may be formed due to fatigue and excessive pressure during the installation and that might cause failure. The hardness values measured near the fracture and in the vicinity of the crack were all greater than 44 HRC. This conclusion is corroborated by comparing it to the hardness of base material which is 39–42 HRC of the plug, which is the magnitude of hardness typically found in tempered 410 martensitic stainless steels using recommended heat treatment practices. But, as at the failed interface, the higher hardness was attained with heavy carbides along the grain boundary. This was attributed due to the improper tempering process of the part. In the present investigations, the attempt is made to determine the type of failure that occurred; the problem appears to involve an improper heat treatment as per the tempering process of the part. In the present investigations, the attempt is made to determine the type of failure that occurred; the problem appears to involve an improper heat treatment as per the metallographic analysis. Furthermore, Finite element analysis (FEM), SEM and ‘X’ ray diffraction analysis (XRD) can be performed to evaluate and explore the detail causes of failure.

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