Remaining life assessment of components subjected to high temperature and corrosion

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Abstract

Remaining life of the components in high temperature service is a need of process industries considering the cost of the new equipment, reliability and safe operation of plants. Equipment remains in operation beyond designed life considering the original safety margins. With advancement in technology and metallurgical knowledge, it is possible to find out the metal degradation behaviour against the life limiting active and potential damage mechanisms. A multidisciplinary approach comprising of metallurgy, NDT, mechanical, fracture mechanics and design can predict the useful remaining life that will provide benefits of economy, safety and reliable plant operation.

(A) Introduction:

High temperature components of the power plants, refineries, and petrochemical, chemical and fertilizers industries are generally designed for 10 to 30 years of life, as per applicable codes and standards pertaining to relevant segment of industries. Normally, the design parameters consider metal properties at the time of manufacturing; however with the exposure of the component at elevated temperature, these properties degrade and undergo ageing effect. This requires re-evaluation of the original design considerations and validating structural integrity for continual operation.

More often, the components survive longer than the design limits. Precisely at this point of time the plant maintenance team would face difficulty in deciding upon the run or replacement strategy. Such decisions, by far, are governed based on past experience and judgement of deciding authority. With increasing knowledge of predictable damage mechanisms and material behaviour,now it is possible to take engineering judgement and validate the remaining life of the component.

Metallurgical considerations are important in selecting an alloy suitable for the operating conditions, both from mechanical stresses and high temperature corrosion point of view. One of the major considerations is degradation in microstructure of an alloy that decides the high temperature properties of the material and its life. Standards and specifications remain silent on the microstructural requirements.However, they put more emphasis on the mechanical properties. An exception is the high temperature creep damage mechanism which is well documented in international standards on the basis of microstructural changes. Remaining life prediction can now be made with reasonable certainty by examining the microstructure of the component and by properly evaluating the changes due to exposure to elevated temperature service.

At high temperature, alloys undergo aging that includes high temperature corrosion. With the knowledge of degradation in microstructure and other relevant high temperature damage mechanisms, it is possible to take a collective judgement on the remaining life of the components. A comprehensive approach to RLA can be formulated in consultation with plant operation, maintenance personnel and metallurgical expert. A team of NDT, corrosion and metallurgical experts can contrive RLA methodology and engineering calculations. Based on quantitative measurements, it becomes possible to predict the damage rate and reasonably accurate remaining life of component.

(B) Damage mechanism and its consideration for Life assessment:

The generally known life limiting damage mechanisms for high temperature components are creep and corrosion. The creep damage has definite relation with stress and temperature, and rate of creep damage can be calculated based on the empirical formulas and microstructure degradation charts. When component is losing thickness at a predetermined rate, its life can be assessed based on other design considerations.

The other potential damage mechanisms are microstructural degradation, high temperature fatigue, creep-fatigue, embrittlement, carburization, hydrogen damage, graphitization, thermal shock, erosion, liquid metal embrittlement, and high temperature corrosion of various types.

Based on given service condition, one needs to identify the potential damage mechanisms. Having done so, the reaming life assessment calculations can be carried out, considering the extentof damage. Many a times it is possible to provide the rerating judgement considering the nature of degradation such that the component can be safely used at a reduced pressure and temperature.

(B.1) Creep damage

At high temperatures, metal components slowly and continuously deform under load below the yield stress. This time dependent deformation of stressed components is known as creep. Creep occurs due to atomic movement of the crystal structure under high temperature and stress, and it results in the creep strain. There is a definite co-relation between the operating temperature and creep damage. With addition of alloying elements in steel the creep resistance temperature can be increased, and hence, high temperature components are made of special alloys. The creep damage can be assessed by microstructural examination- an NDT approach called metallographic replication or in-situ metallography. There are four stages in creep damage. The stage wise degradation is generally observed through microstructurestudy. Vis-à-vis 2nd stage creep and onwards, it is possible to correlate the extent of damage with remaining life reasonably accurate. Figure 1 shows the four stages of creep and concomitant microstructural changes.

The remaining life estimation based on microstructural evaluation is shown in Fig 2, wherein, the vertical axis designates stage of microstructural degradation corresponding to the one shown in Fig 1. The horizontal axis of Fig 2 shows life fraction expended. For example, stage III damage observed as oriented creep cavities on microstructures correspond to nearly 0.6 (or 60%) of life fraction expended indicating balance of 40% as remaining life. Approach to calculate remaining life against creep is through Larsen and Millar Parameter (LMP) which correlates tensile stress to operating temperature and time to exhaust remaining life. The LMP curves data is generally produced by the alloy manufacturers and taken into account at the design stage. However, these curves are equally important for in-service life estimation based on records of operating parameters and accelerated stress rupture test.

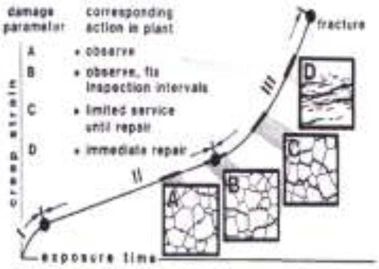

Figure 1

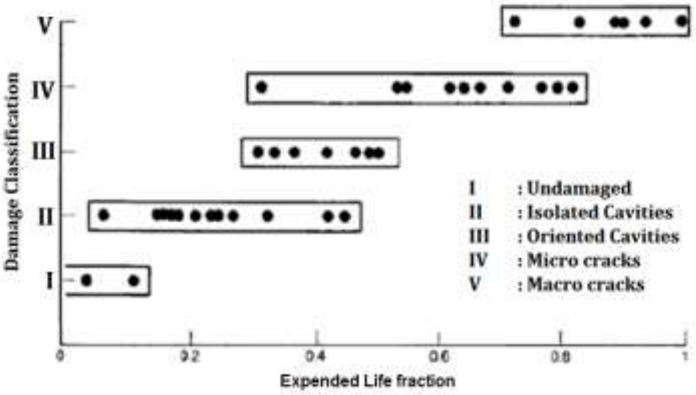

Figure 2

(B.2) Metal skin temperature

The external surface of tubes of heaters and boiler components remain at higher temperature than the internal fluid temperature. The skin temperature of tube is an important governing factor to the actual stresses because of internal fluid pressure. On boiler tubes, scaling occurring at the ID surface would act as a heat barrier. To maintain the heat flux, skin temperature of tube would further increase. Similarly, shift in the combustion zone can as well lead to high operating temperature of the tubes that can accelerate the microstructural degradation.Often high temperature conditions with furnace environment can contribute to reduce the life the component to a much greater extent. Fig 3 shows typical microstructural damage at high temperature.

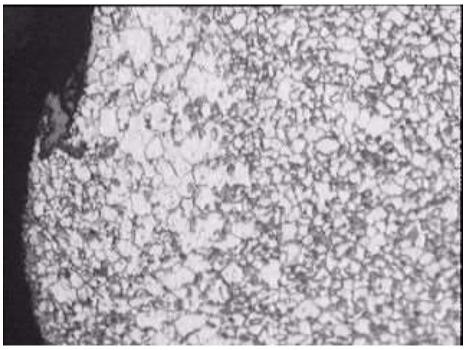

Figure 3 Shows effect of grain coarsening at OD edge on a 660MW Boiler's Water wall tube. The material of construction is SA213 Grade T22. Microstructure shows ferrite and grain boundary pearlite. (200X)

During RLA study it is necessary to understand the prevailing damages, and inspection methodology needs to be decided accordingly. The statutory body for boilers (IBR) has made it mandatory to remove the tube after 100,000 hours of service from the susceptible region and measure the scale thickness across the section, which may be taken as a reference for further destructive tests to compliment RLA study.

(B.3) Corrosion

Corrosion has many forms; normally general corrosion can be predicted based on the process fluids and material used. Actual corrosion rates are calculated based on the periodic thickness measurements, repeated generally on constant locations. The rate of loss in thickness can be calculated and compared with the minimum required thickness after deducting corrosion allowance. Technical module calculations are available to estimate the remaining life based on the nature and type of corrosion that contributes to either general or localized thinning of material. Typical components are shell walls of heat exchangers, tubesheet, tank walls or reactor shells.

Localized corrosion is more dangerous than general corrosion as it might remain unnoticed to confined areas. General forms of localized corrosion are pitting, crevice, under deposit corrosion or caustic gauging. Fig 4 shows one of the localized corrosion form called sulphide stress corrosion cracking.

It is difficult to calculate remaining life of such components accurate enough, where localized corrosion is principle damage mechanism.However,their presence and identification would provide the guidelines to avoid such corrosion and the effective life can be improved.

(B.4) Erosion/corrosion

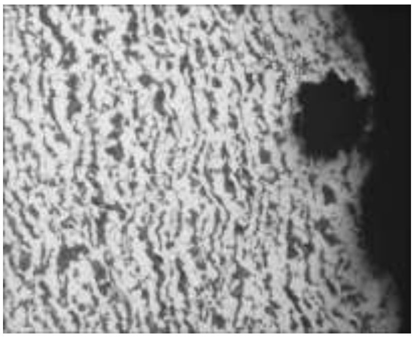

Figure 4 Shows effect of erosion from internal surface on an economizer tube of 300MW boiler side. The material is SA210 Gr C consisting of ferrite and banded pearlite microstructure. (200X)

Erosion-corrosion occurs when corrosion contributes to erosion by removing protective films or scales, or by exposing the metal surface to further corrosion under the combined action of erosion and corrosion. Metal loss rates depend on the flow turbulence, velocity and concentration of impacting medium- for example, particles, liquids, droplets, slurries, two-phase flow, their size, hardness and the angle of impact. The hardness and corrosion resistance of metal is also important. Increasing corrosivity of environment makes the protective film to be unstable and henceforth susceptibility to erosion increases. Metal may be removed from the surface as dissolved ions, or as solid corrosion products which are mechanically swept from the metal surface. This damage is easily identified through visual observation when accessible. Areas of flow diversion like elbow, bends or T joints are susceptible. Microstructural observation under transverse sectional examination would depict erosion as shown in Fig 5.

All susceptible locations may be checked with thickness measurement or with the profile radiography to identify locations of thinning. Thickness monitoring by scanning reasonably large area at bends or on curved piping to trace minimum wall thickness, is a general approach on early warning of erosion/corrosion. Appropriate decision can be taken for design change, material change or process change if the nature of erosion/corrosion is severe or quite frequent.

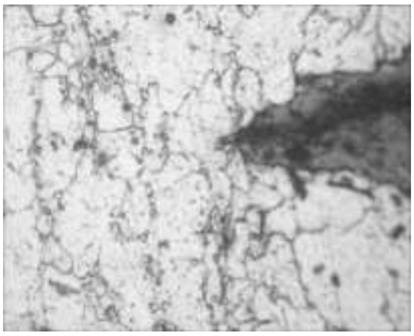

Figure 5 Shows initiation of thermal fatigue cracking on a helical coil used in NMP Extract Solution service of a refinery. The material is SA106GrB. Microstructure shows recrystallized grains with sub grain formation and

(B.5) Thermal Fatigue

Thermal fatigue is the result of cyclic stresses caused by variations in temperature either during operation or at the time of start-up /shutdown. Cracking can occur where relative movement or differential expansion is constrained, particularly under repeated thermal cycling. The vulnerable locations can be identified based on the studying the component design, its metallurgical properties and operational parameters. Some of the components which are highly susceptible to thermal fatigue are heater coils, water wall tubes of boilers, ejector piping assemblies and turbine case tubing.

Typical depiction of thermal fatigue cracks on microstructural examination is shown in Fig 6. The cracks are generally filled with oxide scale and have blunted tips.

Visual examination, DP and MPI are suitable NDTs for detecting thermal fatigue cracks. The life prediction against thermal fatigue cracking is not feasible; hence, it is better to eliminate this damage altogether. Systematic failure investigation to find root cause of thermal fatigue can provide suitable remedial measures to avoid thermal fatigue.

(B.6) Fatigue

It is a mechanical form of degradation that occurs under repetitive cyclic stresses. Normally the component is designed against the fatigue limit; however, under the conditions of localized damage like presence of notches, sharp cuts, weld undercut type defects can act as the stress raisers and initiate the fatigue cracking. On high temperature static pipelines, they are of serious concern, combined with flow induced vibration and start-up/shut down operations when temperature gradients would cause differential stresses. The knowledge of fatigue damage is very important in deciding the area to concentrate in visual examination and selection of other NDT techniques. Technical modules on estimating susceptibility of piping vibration to fatigue failure are well documented by the standards of American Petroleum Industries, which may suitably deployed to estimate service life. Arresting the fatigue cracking in early stage can improve the life of the component and help in eliminating the stress raisers from the system.

(B.7) Embrittlement

The loss of ductility and toughness during the course of fabrication, in-service exposure temperature is indicated by embrittlement. There are several embrittlement mechanisms like temper embrittlement, 475°C temperature embrittlement, Sigma phase embrittlement, liquid-metal embrittlement and hydrogen embrittlement. All embrittlement mechanisms increase susceptibility of the equipment to failure under brittle mode and can lead to catastrophic consequences. All embrittlement mechanisms are occurring due to metallurgical change in the material. Typical presence of sigma phase in grade 300 stainless steels is shown in Fig 7.

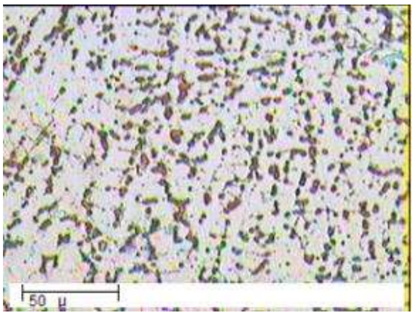

Figure 6 Shows copious sigma phase formation at austenite dendrites in weld of SS304H used for NG Lateral in Hydrogen service in refinery.(1000X)

The temper embrittlment can be controlled by adopting good steel manufacturing practice by controlling tramp elements. Whereas materials selection plays an important part in avoiding 475°C and sigma phase embrittlement. Liquid metal embrittlement occurs due to low melting point metal coming in contact with equipment at high temperature.It penetrates the grain boundaries and makes the material brittle. Hydrogen embrittlement occurs due to diffusion of hydrogen in the steel due to process conditions or as by-product of corrosion. Based on the experience of a metallurgist undertaking RLA study, one can predict the susceptibility.

(B.8) High temperature hydrogen attack

When hydrogen enters in to steel at elevated temperature and pressure, it combines with carbon and forms a methane gas. All those equipments handling hydrogen gas above 200°C temperature are susceptible for hydrogen attack. The damage is associated with loss of carbon as well forming a micro fissures at the grain boundaries as shown in Fig 8.

However, susceptibility of high temperature hydrogen attack depends on the material of equipment as well. Carbon steel and low alloy steel grades are more susceptible to hydrogen attack. As the alloying elements like chromium and molybdenum increase in steel the resistance to hydrogen attack increases. Identifying the correct inspection technique and location of damage for inspection during remaining life assessment is key factor

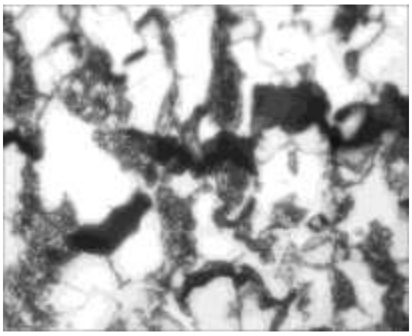

Figure 7 Shows scattered micro crack network preferentially on pearlite colonies, discontinuous in nature on a 0.2% carbon steel water wall tube of a 300MW boiler. (1000X)

(B.9) High temperature corrosion

There are several corrosion mechanisms that occur at high temperature, like oxidation, sufidation, carburization, metal dusting, decarburization, fuel ash corrosion and nitriding. The corrosion occurs at particular rate and that is possible to determine by the depth of attack. Through the approach of periodic inspection of components by DPT or fluorescent DPT, thickness monitoring it is possible to identify the nature of damage and its susceptibility to the material. An example of a gas turbine bucket is shown in Fig 9.

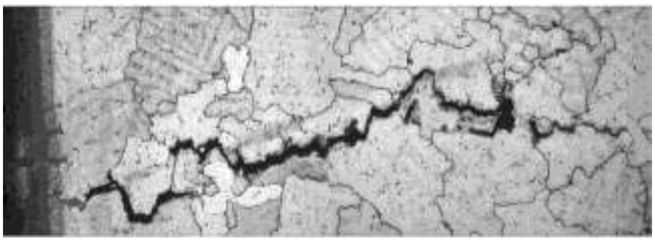

Figure 8 shows a panoramic view of the crack initiated from an edge over the protective coating and propagated across the grains in intergranular mode on a 1st stage bucket of 10MW gas turbine. The material is IN 738; microstructure shows grains of nickel solid solution. (400X)

Once the onset of damage is observed, increased frequency of inspection to predict the remaining life requires to be done. However, removing a sample piece from the base component, if feasible, would certainly narrate the depth of attack. For example, on OD or ID under attack, destructive techniques with possible simulation at the laboratory one would be able to determine the rate of damage with accuracy in short time. The life of the equipment may be judged based on this consideration.

(C) Conclusion

All of the above damage mechanisms correspond to high temperate components and their role and knowledge of their damage rate is vital in predicting the accurate remaining life. The approach and success of RLA depends on the identifying the active and potential damages to the equipment and selection of correct NDT for particular damage. The team participating for RLA activities should be well aware of component design and metallurgy involved. It is of utmost importance to form a team of metallurgists having knowledge of damage mechanism, NDT inspection engineer,the design and process experts.

The outcome of RLA, many a times reveals vital information that facilitates verification and recalculation of the design considerations based on loss of thickness, mechanical properties having proper safety factors. With the scientific and engineering approach to the degradation of properties through fracture mechanics approach, it is possible to predict the allowable flaw size that can permit the equipment to be put into service safely. The advanced knowledge will help industry to get the extended life of the component and avoid its unnecessary replacement. At the same time, one can identify the potential concern areas in the equipment that may be addressed during shutdown, and reliability of the equipment can be improved. If the study indicates unsafe conditions it will help to take the decision on retiring the equipment.

Considering the factor of safety in original design and with history of plant operation, it is possible to judge the life of equipment with multidisciplinary approach. In India most of the plants are ageing and have consumed their designed life. With modern technology and knowledge in the field of metallurgy, NDT, fracture mechanics and design, one can optimize the operational life of the equipment which can be considered extension of life, increase in safety and reliability of plant.

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