AN OVERVIEW OF FAILURE MECHANISMS IN HIGH TEMPERATURE COMPONENTS IN POWER PLANTS

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ABSTRACT

The principal mechanisms of failure of high temperature components include creep, fatigue, creep-fatigue and thermal fatigue. In heavy section components, although cracks may initiate and grow by these mechanisms, ultimate failure may occur at low temperatures during startup-shutdown transients. Hence, fracture toughness is also a key consideration. Considerable advances have been made both with respect to crack initiation and crack growth by the above mechanisms. Applying laboratory data to predict component life has often been thwarted by inability to simulate actual stresses, strain cycles, section size effects, environmental effects and long term degradation effects. This paper will provide a broad perspective on the failure mechanisms and illustrate a few of the typical ones in boilers.

KEYWORDS:

Creep, Fatigue, Thermal Fatigue, Boilers, Steels, Fracture Toughness

1.0 INTRODUCTION

Reducing the cost of power production is paramount for staying competitive in the emerging utility market. Reducing capital costs by deferring replacement of expensive components and reducing operating and maintenance (O&M) costs by optimizing operation, maintenance and inspection procedures will both be key strategic objectives for utilities. This poses a significant challenge to the technical community since two apparently opposing needs will need to be reconciled. On the one hand, the need for improved plant efficiency and availability will dictate more severe and cyclic duty schedules which result in more severe creep-fatigue damage and warrant increased attention to the components. On the other hand, the need to reduce O&M costs may result in fewer, shorter and lower quality maintenance and inspection outages; thus, placing the components at greater risk of failure. The challenge to the technical community, therefore, is to develop tools and techniques that will permit more rapid, cost-effective and accurate assessment of condition of critical components, both off-line and on-line. In addition to assessing the current condition, these tools must also be capable of evaluating the impact of alternative strategies for operation, inspection and maintenance. It is crucial therefore that the high temperature research community be more intimately familiar with the specific needs of the industry. This paper will bring out some of the industry perspectives regarding high temperature failures and illustrate them with some failure examples pertaining to creep and thermal fatigue. A detailed review of the failure mechanisms affecting the integrity of utility and chemical plants can be found in Reference 1 [1]. Some critical industry perspectives are reviewed in detail in Reference 2 [2].

2.0 EXAMPLES OF HIGH TEMPERATURE FAILURES

Failure mechanisms at high temperatures include creep, thermal fatigue, corrosion, erosion, and hydrogen attack. In addition, embrittlement phenomena occurring at high temperatures, e.g. carbide coarsening, sigma phase formation, temper embrittlement, etc. can facilitate rapid brittle fracture at low temperatures during transient conditions. This section will describe issues associated with creep, thermal fatigue and embrittlement. Mechanisms affecting the integrity of fossil power plants may be found in Refs. 1and 2 [1,2].

2.1 Creep

Creep damage can take several forms. Simple creep deformation can lead to dimensional changes that result in distortions, loss of clearance, wall thinning etc. Examples are steam turbine casings, blades, and piping systems. Localised deformation can cause swelling and eventual leaks in headers, steam pipes and superheated reheater (SH/RH) tubes. Long term creep failures generally tend to be brittle failures involving cavitation and crack growth at interfaces and at highly stressed regions. The cavitation form of damage has been found in SH/RH tubes, rotor serrations, occasionally rotor bores, highly stressed areas in piping systems and at weldments. The most common weld failures have pertained to dissimilar welds in superheater/reheater tubing, welds in headers and in hot reheat and mainsteam piping.

2.1.A Failures in Headers at Girth Welds: A schematic illustration of a header is shown in Figure 1.

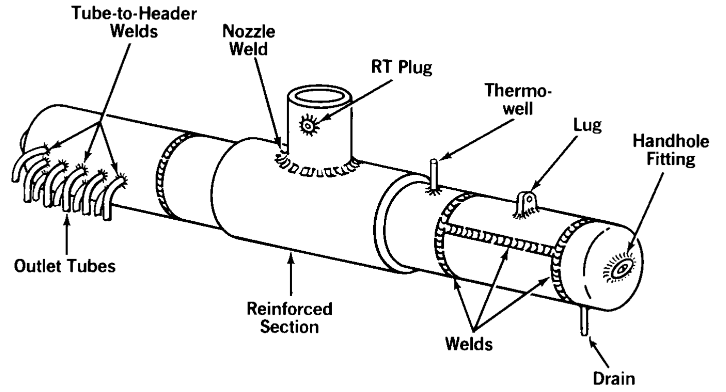

Figure 1: Schematic illustration of an elevated-temperature header (courtesy of B. W. Roberts, Combustion Engineering, Inc.)

Initial signs of creep-related distress in headers often appear at welds—welds at stub-tube inlets, long seams, header branch connections or girth butt joints. With the exception of some cases of long seam welds, and Type IV cracks in girth welds, creep damage in welds is invariably manifested on the outside surface as cavities, cracks, or, in extreme cases, steam leaks. Except in regard to long seam welds, concern about catastrophic bursts has been minimal. Although weld-related cracking is generally detectable and repairable, and although it does not have as great an impact on the over-all component life as does header-body base-metal deterioration, it is important from a life-assessment point of view for the following reasons: Because weld failures are often the forerunners of damage in the body, they can provide an index of creep damage and remaining life in the base metal. Failure of welds at crucial and multiple locations may constitute the end of the life of the header, regardless of the condition of the base metal. The need for frequent weld repair may prove uneconomical and justify retirement of a header. Due to these reasons, creep-damage assessment of welds has received considerable attention.

Four types of creep damage and cracking associated with weldments (for both headers or piping) have been cataloged by Chan et al. [3]. Each of the four creep damage types are identified below and shown schematically in Figure 2.

Type I — Damage which is longitudinal or transverse in the weld metal and remains entirely within the weld metal.
Type II — Damage that is longitudinal or transverse in the weld metal, but grows into the surround HAZ.
Type III — Damage in the coarse-grained region.
Type IV — Damage initiated or growing in the intercritical zone of the HAZ (the transition region between the fully-transformed, fine-grained HAZ, and the partially-transformed parent base metal).

Both axial and circumferential cracks have been observed in damaged girth butt welds, with cracking being found in the weld metal and/or the HAZ. The axial cracking has been attributed to internal pressure loading and pipe swelling, whereas the circumferential cracking has been associated with combined pressure and piping system loads. Several instances of girth weld cracking has been reviewed [4]. In one instance, circumferential cracking along the coarse-grain HAZ was attributable to stress-relief cracking prior to service. Axial creep cracking across the weld metal has been attributed to a combination of pipe swelling and poor weld ductility. Circumferential cracking in the intercritical regions of the HAZ has also been observed in both Cr-Mo-V and Cr-Mo steels. This type of cracking, known as Type IV cracking, occurs at the end of the HAZ adjacent to the unaffected parent metal. Type IV cracking is generally attributed to localized creep deformation in a "soft" zone in the intercritical region under the action of bending stresses. Field experience suggests that Cr-Mo-V steels may be more susceptible to cracking than Cr-Mo steels and that operation at 565°C (1050°F) rather than at 540°C (1000°F) might further exacerbate the problem. Because most of the headers in the United States are made of Cr-Mo steels and operate at 540°C (1000°F), the problem has not been encountered to any significant degree. More recently, Type IV cracking is emerging as a concern for P91 piping.

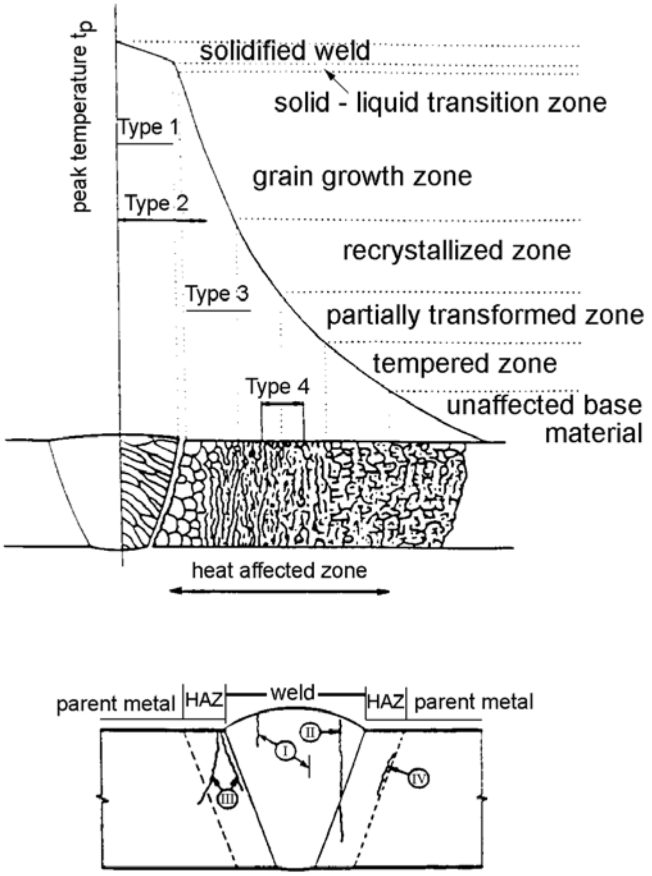

Figure 2: Four types of damage in girth welds in relation to microstructure [3].

2.1.B Failures in Seam Welded High Energy Piping:

Several categories of pipes carrying high temperature/pressure steam contain welds that may be of concern. Main steam pipes are pipes that carry steam at 538-565°C to the high pressure turbine. These pipes are small in diameter and do not contain seam welds. Hence, only girth welds are of concern. The mainstream pipes are however, often connected to the steam header using thick-walled seam welded piping. In addition, hot reheat pipes which carry steam at 538-565°C but at a lower pressure (than the main steam pipe) to the reheat IP turbine, and are frequently made of seal welded piping. Failure of seam welded pipes used in HRH piping as well as in header link piping has been of major concern to industry. Failure experience with respect to high energy piping has been reviewed by Wells and Viswanathan [5]. There have been at least 17 major instances of seam welded pipe failures including 3 cases of catastrophic rupture, 5 leaks and 9 incidents of major cracking. The failures are generally brittle with a fish mouth appearance.

In the cases of HRH pipes, the welds generally have a double V configuration and the pipes are generally subjected to a normalizing and tempering treatment. The cracking generally initiates subsurface at the cusp of the double V and then propagates along the fusion line towards the outside and inside, as shown in Figure 3. In the case of the thicker walled header leak pipes, the weld generally has a U geometry and is subjected to subcritical PWHT. A variety of cracking modes, including fusion line, Type I and Type IV cracking have been observed. Failures of most of the seam welded piping have occurred prematurely and could not be predicted based on simple life-fraction rule calculations. Failures occur due to unique combination of operating and metallurgical variables. Some of the contributing factors have been identified to be operating temperature, pressure, cycling system stresses, and weld geometric factors such as configuration, cusp angle and roof angle, and welding practice employed; inclusion content and creep strength mismatch, etc. Currently two failure scenarios have been postulated. In one scenario, failure is proposed to involve crack initiation and propagation stages. In the alternative scenario cavities form and grow and eventually link up into a larger crack. Which of these is operative can determine whether NDE based monitoring is viable. A comprehensive review of the subject may be found elsewhere [6-8].

Since in many of the early instances of girth weld damage, the damage has consisted of evolution of creep cavities into cracks at the coarse grained heat affected zone (CGHAZ), assessment of damage consisted of simply classifying the damage and then recommending an appropriate action. Damage was classified as (A) isolated cavities, (B) oriented cavities, (C) linked cavities and (D) microcracking, as per the German practice. More quantitative correlations between the degree of cavitation and the creep life expended have been established based on EPRI research and have provided a clearcut basis for establishing re-inspection intervals. This approach is however valid only for Type III cracking in the CGHAZ. The evolution of damage in the other cases have not been sufficiently investigated.

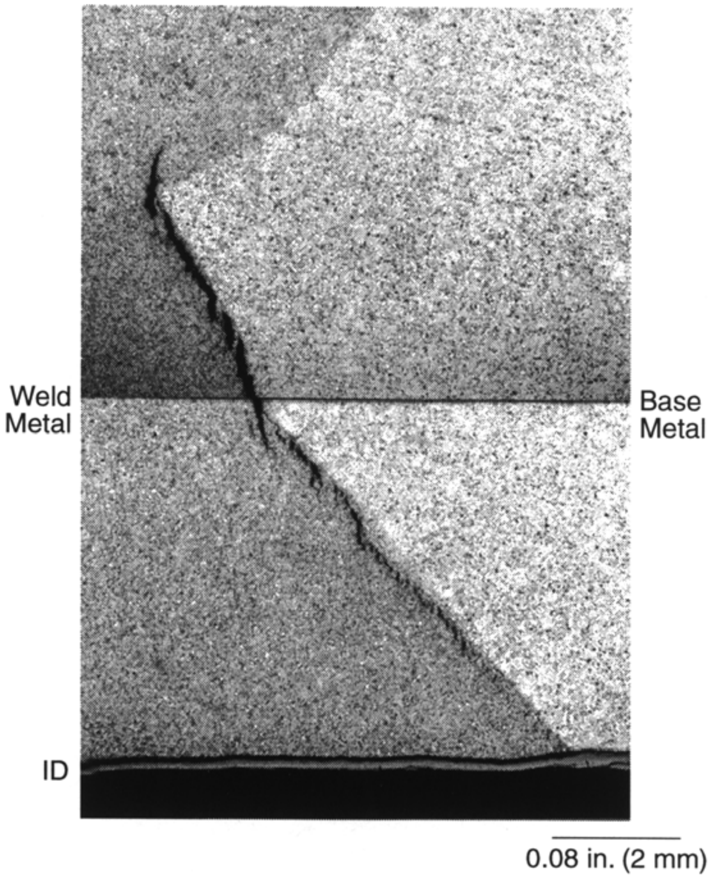

Figure 3: Macrograph of cross-section at location 6LS1, counter-clockwise side of weld sighting along flow; note ID-connected-cracking, located and detected by UT, and extent of cusp damage.

While replication is very useful for detecting surface damage, many types of failures such as long seam weld and Type IV damage in girth welds originate sub-surface. In these cases, replication alone is not a reliable method to detect damage. In long seam welds in hot reheat piping and header link piping, high sensitivity conventional or automated UT, focused beam UT or time-of-flight diffraction UT methods are needed to ensure safety of the piping. In the case of girth welds however, conventional UT seems to be adequate.

Some forms of creep damage are more manageable than others. For example, if Type I, II or III creep damage is found, the subsequent action can range from record and monitor to some form of repair depending on the severity of damage. Advanced Type IV damage is characterized by profuse intergranular cavitation in the creep weak area of the HAZ. It has been suggested that the evolution of damage from the observation of cavitation (by replication) to macro-cracking can be swift and cannot be dealt with using the German system. In the absence of enough experimental evidence regarding damage evolution, the current approach is to replace completely the affected weldment, if any stage of Type IV damage is confirmed.

3.2 Creep-Fatigue Failures

Creep-fatigue damage induced by thermal stresses is of major concern with respect to the integrity of many high temperature components. The concern has been exacerbated in recent years due to cyclic operation of units originally designed for base load service. A sample list of fossil plant components in which creep-fatigue has been a dominant failure mode has been published in Reference 2. A common form of cracking known as "Ligament Cracking" is described below.

Ligament cracking encountered in CrMo steel header pipes illustrated in Figure 4. Cracks initiate in the tube bore holes and are oriented parallel to the axis of the tube bore hole. Linking up of cracks between holes on the inside surface of the header leads to propagation to form cross ligament cracks. Presence of ligament cracking has been observed in a very large number of superheater headers in the U.S. The cracking mode has been identified as creep fatigue. A computer code, Boiler Life Evaluation and Simulation System (BLESS) developed recently, incorporates two alternate approaches for predicting crack initiation; one involving an inelastic linear damage summation method, and a second approach involving repeated cracking of oxide scale and oxide notching[9]. For a variety of cycle histories, the Code predicts crack initiation occurring in about 20,000 h by the oxide cracking mechanism. The creep-fatigue damage summation approach on the other hand, is inconsistent with the early initiation of cracks observed in headers. Metallography of cracked headers has shown numerous oxide spikes, see Figure 5, indicating oxide cracking to be the crack initiation mechanism. This example clearly illustrates the need for using appropriate thermomechanical fatigue data simulative of actual component cycles in predicting crack initiation life of components.

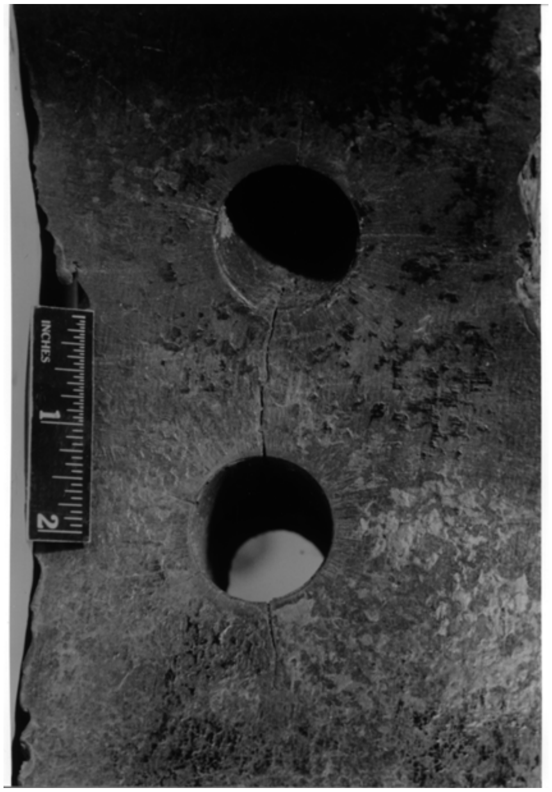

Figure 4: Ligament cracking at a tube bore hole viewed from the ID of a header.

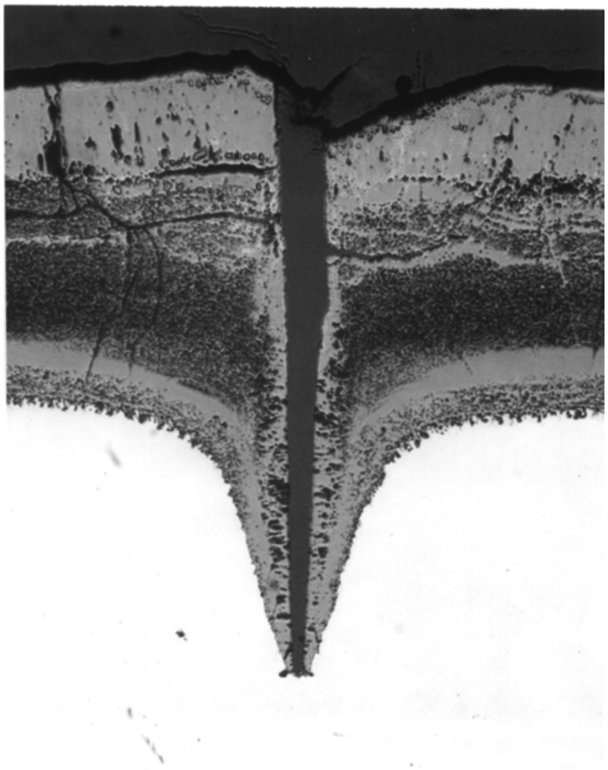

Figure 5: Oxide notching at ligament cracks.

4.0 SUMMARY AND CONCLUSIONS

Creep and creep-fatigue are the principal failure mechanisms affecting the integrity of components operating at elevated temperatures. Creep damage in weldments poses major challenges both in analytically calculating it and in experimentally reproducing it. Several alternative damage locations and mechanisms have been observed which are often difficult to reproduce in laboratory tests. Fusion line cracking and fine grain heat affected zones (FGHAZ) cracking has led to catastrophic failure of high energy piping. Thermomechanical fatigue (TMF or creep fatigue) affects many heavy section components as well as internally cooled components such as combustion turbine blades. It is important that researchers focus on component specific (rather than generic) life prediction models with a full understanding of the applicable failure definition, failure scenario and relevant duty cycle. Future research needs to address advanced NDE techniques, on-line monitoring techniques, TMF mechanisms, and evolution of damage and growth of cracks in welds.

5.0 REFERENCES

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