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Premature Grade 91 failures — worldwide plant operational experiences

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ABSTRACT

Four different case studies of premature failures of Grade 91 materials in Heat Recovery Steam Generators (HRSG) and power piping at combined cycle power plants throughout the world are described. The impact of plant design, the metallurgical aspects of the failures and results from finite element simulations are incorporated. The failure modes discussed are brittle, creep failure, creep and creep-fatigue (CF) failures. All of the investigated cases had life calculations showing a creep life greater than the intended service life of the components. However, since all cases suffered pre-mature failures, it can be concluded that sufficient design life using design temperature and hoop stress is not a guarantee for safe design. The failures can be accredited to improper material properties associated with deficient fabrication and Post Weld Heat Treatment, increased service loading due to geometrical effects not included in design calculations and increases in local temperatures due to gas turbine (GT) load changes. Recommendations to mitigate the risk of component failures are presented.

1. Introduction

Early failures of components fabricated with Creep Strength Enhanced Ferritic (CSEF) Steels in conventional and HRSGs in combined cycle plants have gained widespread attention within the industry. Affected HRSG components included boiler tubing and interconnecting piping as well as non-boiler external piping.

CSEF steels such as SA335 Gr. P91 in piping and T91 in boiler tubing (often referred to collectively as "Grade 91") have been used at many new large combined cycle power plants. Welding of this material requires careful attention; the correct welding technique, weld filler materials and strict adherence to pre- and post-weld heat treatment requirements must be applied [1]. Proper heat treatment is essential in order to obtain the desired enhanced creep resistance. Special problems can arise when Grade 91 components are welded to dissimilar materials. Dissimilar metal welds (or DMW) between P91 and P22 or P91 and stainless steel have been particularly problematic at some plants.

This paper presents four case studies of premature Grade 91 materials in Heat Recovery Steam Generators (HRSG).

2. Background

Use of Grade 91 steel in high temperature steam components including pressure vessels is attractive because they provide a superior level of creep (and fatigue) strength and oxidation resistance at elevated temperatures. The steel is a martensitic Cr-

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Mo steel that has been microalloyed with vanadium and niobium and has a controlled nitrogen content. After welding, brittle martensite with unfavorable material properties is formed in the weld metal. Thus, heat treatment is required in order to produce tempered martensite with precipitated carbides and vanadium/niobium-rich carbo-nitrides which provide for acceptable material properties. Industry-recognized standards for PWHT parameters of Grade 91 steel currently dictates an ideal temperature of 760 °C for 2 hours [1,2], maintaining these precise conditions during actual fabrication requires careful control. Therefore, an understanding of the allowances for variation in the PWHT parameters must be developed in order to ensure that the final mechanical properties of the steam pressure vessel will meet design requirements.

The most common type of Grade 91 creep failure is the so called type IV failure, where cracks develop and progress in the fine grained Heat Affected Zone (FGHAZ). This part of the weld has reduced creep strength properties, hence creep is likely to originate here.

Despite superior material properties, in-service failures have been reported in literature. One of the most well-known cases occurred at the 4 × 500 MW coal-fired power station West Burton in the UK [3,4], where failure was reported after as little as 20,000 to 36,000 h of service. Failures were attributed to degraded material properties and increased stress levels due to the geometry of the failed component. Additional in-service experience of Grade 91 failures have recently been reported by EPRI [5]. The root cause of more than half of the investigated failures could be related to either poor design or poor fabrication.

3. Methodology

Metallurgical investigations have been performed on all four failed samples in order to determine damage mechanism, microstructure and mechanical/chemical properties. Heat treatment data was reviewed where it was available. Creep life calculations have been performed based on the BS:EN 12952-4 [6] in-service boiler code, using design pressures and temperatures. The Larson-Miller Parameter (LMP) was used to analyze ECCC [7] creep stress vs rupture time data. A third order polynomial curve fit of the LMP and logarithmic stress was used. The lower limit curve of the creep rupture scatter band was used per BS:EN 12952-4 [6]. The following relation has been used for the creep life calculations:

$$LMP = (T + 273)(\log(t_r) + 31.2) = -2,275\log(\sigma)^3 + 9,888\log(\sigma)^2 - 19,877\log(\sigma) + 49,143$$

where T is temperature (°C), t_r is rupture time (h) and σ is the stress (MPa).

In addition, curves using Weld Strength Reduction Factors (WSRF) as multipliers to the creep rupture strength were also derived. The WSRF used are decreasing with increasing temperature, starting at 1.0 for temperatures below 550 °C, varying almost linearly to 0.7 for temperatures at 650 °C, as proposed in [8]. WSRFs have also recently been incorporated into the ASME boiler code. Mid wall hoop stress is the primary stress used in calculations.

In addition, to take geometrical stress raisers into account Finite Element Analysis (FEA) has been applied to the plant B case using the commercial simulation tool SolidWorks Simulation (2015). The mesh density was kept sufficiently fine (<2 mm) at locations of higher stresses, internal pressure was applied as loading, and the through wall hoop stress distribution was compared to analytical calculations of the hoop stress. The resulting increase in stress, or Stress Concentration Factor (SCF), is defined as the ratio between the simulated stress level and the analytical stress level. This increase in stress was used in the modified creep life calculations for comparison to the nominal stress approach (mid wall hoop stress).

The design data used as input to the creep calculations can be seen in Table 1.

Table 1
Design Data.

Plant	OD	Wall thickness	Design pressure	Design temperature
	[mm]	[mm]	[MPa]	[°C]
A	711	21.5	5.27	574
B	355.6	38.1	13.6	569
C	323.9	21.5	10.5	550
D	31.8	2.8	11.6	602

4. Plant A — hot reheat (HRH) laterolet — USA

4.1. Background

Plant A is a 2 × 1 natural gas-fired combined cycle power plant that was commissioned in early 2002.

The first large scope inspection of Grade 91 at Plant A commenced during the scheduled spring outage in 2011. At that time, the plant had operated for >25.000 h. Large cracks were easily identified by UT Shear wave on both sides of one of the lateral fittings, Fig. 1. The cracks were long and relatively deep, but were not through wall, Fig. 2. In addition, structural damage to pipe support structural steel was evident on one pipe support that is very close to the lateral (horizontal lateral restraint).

Inspections of the main run-branch fitting and the second unit branch to lateral fitting welds were also conducted in October 2011, November 2012 and November 2013. In October 2014, a small leak was identified in the vicinity of the HRH lateral. The