Abstract

The structural integrity of seam-welded fossil high-energy piping has remained a major safety and operations-maintenance issue for US utility companies. Several failures of seam-welded superheat and hot reheat piping segments have occurred since 1992, two of them catastrophic. Advanced methods of inspecting piping welds with ultrasonic testing (UT), such as time-of-flight diffraction and focused/phased arrays, are pushing back the envelope of detection to earlier stages of creep damage, but these are still very expensive, and involve considerable logistical planning and downtime to perform. The Electric Power Research Institute (EPRI) has sponsored development activities since 1986 to mature the utilization of a real-time online evaluation method for seam-welded piping: Acoustic emission (AE) testing guidelines were published by EPRI in 1995, and over 100 full-scale tests have been performed to develop a database and correlate results with other established evaluation methods. An effort was begun in 2002 to standardize the testing method within ASTM (AE Subcommittee of E07.04) utilizing the developed database. Tests to date have shown high sensitivity to early stage creep damage, which is evidenced by development of cavities around inclusions in the grain boundaries. Successful double-blind testing with advanced ultrasonic inspection methods has proven both the reliability and sensitivity of the AE technique. The economics of the method are highly favorable. Only small areas of insulation need to be removed every 4.6-6 m to weld waveguides to the piping surface. These form a linear location array along the length of piping, providing global coverage of the piping system. Testing is performed online with normal peak loading and load cycling. No outage schedule is required to perform the AE examination. Results will be presented showing that the AE method has become a reliable and economical field evaluation tool for seam-welded high energy piping.

Keywords: Seam-welded piping, fossil power plants, online monitoring, high temperature creep

Introduction

Ever since the catastrophic failures of seam-welded, hot reheat (HRH) piping at Southern California Edison’s Mohave plant in 1985 and Detroit Edison’s Monroe plant in 1986, utility companies have been carefully considering the need for periodic inspections of critical piping to guard against creep-induced failures. Figure 1 illustrates the creep-damage mechanisms associated with seam-welded, high-energy piping. A number of serious defects in seamed piping were removed after inspections in the late 1980’s, and for a number of years there were no more catastrophic failures [3]. Beginning in 1992, however, there have been six known failures of seam-welded superheat (SH) link piping supplied with Combustion-Engineering boilers, as well as two failures in hot reheat long seamed bends. Two of these have been catastrophic: Virginia Power’s Mt. Storm Unit 1 in June 1996, and Kansas City Power & Light’s Hawthorne Unit 5 in August 1998. No loss of life occurred in either of those two failures, but the cost of repairs and loss of power generation is of critical concern to utility companies in this age of growing competition. All failures of SH link piping have occurred on units with accumulated service time of
Fig. 1. Typical high-temperature creep damage occurring in seam-welded fossil piping systems constructed of P11 or P22 grade steels [3]. Type IV damage in the fine-grained HAZ typically occurs in subcritically annealed welds, which is more typical of thick-section SH link piping and some HRH piping.

Fig. 2 a) Micrograph showing cavitation damage in the cusp region of an HRH double-V weld [4]. b) Micrograph showing advanced damage in the form of microcracks from a failed long seam bend [5].

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125,000 to 225,000 hrs. Figure 2 shows micrographs of cavitation damage and advanced damage of microcracks from a failed long seam bend [4, 5]. These are truly microscopic defects. Compounding the problem of inspection is the inaccuracy of supplied documentation, which may not reflect the true alloy content and method of fabrication. The Hawthorne SH link piping
was not known to be seam-welded. The general aging of fossil plants will continue to raise concerns about the safety of operating seam-welded high-energy piping systems. Even seamless piping systems have had problems, including creep-related failures of circumferential welds, and the through-wall creep failure of a seamless SH bend that had been improperly fabricated. Current strategies for effectively managing the safety and life of seam-welded piping are based upon periodic inspection of the weld area for evidence of in service damage.

**Equipment and AE Testing Set-up**

The process of AE monitoring applied to piping systems starts with installation of AE transducers on welded waveguides (WG) along the length of the piping system. Spacing intervals for the WG are typically 4.6-6.1 m (15-20 ft), and installation of the sensors does not require full removal of piping insulation. There are several unique requirements for successful monitoring of high-energy piping with AE [1, 2]:

- The use of high-frequency sensors (300-400 kHz) and high frequency filtering (>200 kHz) to mitigate the effects of the steam-flow background noise. This noise is predominant below 300 kHz, and would obscure detection and accurate source location if lower-frequency, or broadband, sensors were used.
- The employment of a “floating” or automatic threshold that can control the sensitivity of detection by keeping the voltage threshold of detection above the average background noise.
- The use of active linear source location to determine the position of emitting sources on the line. The accuracy of location is dependent on the distance between sensor/waveguide positions, the pipe diameter, and the position of the emitting source. In the middle of the array between two sensors, accuracy has been demonstrated at ±2.4 cm (±0.6”). Near the sensors accuracy may degrade to ±60 cm (±24”). Still, this limits areas for follow-up inspection.
- The use of active AE-signal-feature filtering to further refine the data and eliminate obvious noise sources, such as flow turbulence. Rise time, duration, and average frequency have proven most valuable.
- Simultaneous recording of piping temperature and pressure are required to provide correlation between active AE sources and the likely source mechanisms.

**Data Evaluation and Correlation**

The primary characteristics of seam-weld creep-related sources are behavioral in nature—they respond to the pressure in the piping (hoop stress) and other mechanical sources of stress (geometry, hanger supports, etc.). During online conditions with normal peak load cycling, creep-related sources reveal themselves by repeated behavior with each peak load cycle [2]:

- The sources are sensitive to pressure, and may show a pronounced effect of emission rate with pressure (Figs. 3, 4).
- During load cycling, emission rates will typically peak near the start of the peak-load period.
- There is periodic emission activity during steady-state pressure and temperature conditions.
- The AE location profile is typically spread out over 1 m (40”) or more of piping length, and shows intermittent high-density locations of activity (Fig. 3).
- The amplitude range of emission sources broadens to higher values with higher activity rates (Fig. 2).
• Emission rates are much higher during startup conditions, even before substantial pressure loading. This demonstrates that the damaged area is responsive to stresses even when the piping is not in the creep regime (>510°C, 950°F).

Fig. 3. A seam-welded clamshell elbow on Illinois Power’s Baldwin #2 HRH line shows typical creep-related AE behavior under cyclic pressure loading (upper left). The mechanism shows high sensitivity to load, and shows a distribution of activity along the elbow that varies with each load cycle (lower left). Bottom right shows the amplitude density feature map of this elbow location. Distributed higher activity sources are evident, and the amplitude dynamic range is larger in the high activity area. Defect growth at this early stage is probably related to decohesion of inclusions that are being affected by the creep process.

The amount of emission generated by the creep mechanism, the repetitive nature with each peak load cycle, and the extensive dynamic range (45-90 dB amplitude) of signals, is extraordinarily different from normal ductile fracture mechanisms, such as fatigue crack growth in mild steels. Many thousands of locatable signals are sometimes accumulated over 1 m or so of weld length and several cycles (days) of steam line operation at peak load. The sheer numbers of the sources is inconsistent with a ductile crack growth mechanism, which produces infrequent emission of more limited dynamic range with repeated load cycles. The acknowledged mechanism of
Creep in seam welds is the development of cavities (cavitation) around nonmetallic inclusions and carbides on the grain boundaries in the fine-grained heat affected zone (HAZ) or fusion zone of the seam weld (Fig. 1). Isolated cavities soon give way to aligned cavitation along grain boundaries, then coalescing into scattered microcracks. Final consolidation and linking into macrocracks along the seam-weld direction occurs in the last stage of growth, which can be very rapid depending on a host of factors (wall thickness, annealing state, inclusion densities, thermal and localized mechanical stresses, etc).

Fig. 4. Results of AE monitoring of the Ghent #1 East HRH link piping. a) Configuration. b) The linear source location plot shows three AE clusters detected (A, E, B).
Fig. 4. Results of AE monitoring of the Ghent #1 East HRH link piping. c) A composite graph of plant parameters and AE source location vs. time for the three clusters detected. The pressure sensitivity of the sources is obvious, marking them as creep-related sources. d) The relative activity in events/inch-hr at different pressures for Cluster “A” in the original monitoring program. After through-weld repair of the piping, the activity drops by >90% for this area, indicating that the original sources of emission have been removed.
The early stage of this process involves the degradation of the bonding between particles and the metal matrix. These are load-carrying interfaces, and their eventual failure (decohesion) is the most plausible explanation for the amount and dynamic range of emission detected in the creep process. From the viewpoint of classifying AE behavior, this bears similarity to the experience of monitoring an organic-based composite material that has incurred extensive matrix damage. This also explains the emission that has been noted during the thermal excursion on startups, even without pressure in the system, when the piping is clearly not operating in the creep range. Damaged particle-to-matrix interfaces are prone to disbonding under high strain conditions, and startups are known to produce an even higher axial strain than at full load operation. Indeed, the results of the extensive EPRI field testing program to date has yielded detection of cavitation damaged seam welds that have not developed to the stage of micro- or macro-cracking.

A separate test program conducted in collaboration with a UK utility demonstrated that controlled creep-crack growth in small specimens produced increasing emission with increased crack growth rate. The emission rate was orders of magnitude higher for the increment of crack growth than would have been expected at lower temperatures and growth under fatigue conditions. The decohesion mechanism remains active throughout the creep regime, regardless of whether induced by directed stress at the tip of an active crack or in a volume of weld without visible cracking. This leads to high probability of detection of the creep-related failure process from very early stages, well before the damage represents a significant threat of structural failure.

Correlation of AE findings on seam-welded lines with other NDE methods and metallography were an important part of the EPRI studies and field tests from 1991 to 2001. Double blind testing was performed on Pacific Gas & Electric’s Potrero #3 line in 1994, American Electric Power’s Gavin #1 line in 1996, and Sierra Pacific Power’s Valmy #2 line over 1997-1999. In these tests good correlation was established between conventional automated and manual multiangle UT methods and AE cluster locations in seam and girth welds. But metallography was not used extensively in these tests to confirm the nature of the indications. Later testing would provide more extensive correlation between AE and advanced UT methods (TOFD, Phased Array, Focused Array), and more sensitive metallographic analysis (cryo-cracking with SEM examination). These included programs on Kentucky Utilities Ghent #1 HRH line and Brown #3 SH link piping (1997-98), Central Power & Light’s Joslin #1 HRH line (1997), Illinois Power’s Baldwin #1 HRH (1998), Salt River Project’s Navajo #2 HRH line (1998), Southwestern Public Service Co’s Harrington #2 HRH line (1999), and Portland General Electric’s Boardman HRH line (2001).

By the late 1990’s it was becoming better understood that creep damage in seam welds did not initiate as distinctive crack-like flaws, but rather as an accumulation of microstructural damage evidenced by “cavitation” development around inclusions and carbides along the grain boundaries in the heat affected zone or fusion zone of the seam weld (depending on whether the structure was normalized and tempered or subcritically annealed after welding). Several high-profile failures of seam-welded piping after missed or misinterpreted UT findings (Sabine #2 HRH bend in 1992, Mt. Storm #1 SH link piping in 1996, Gaston #4 HRH bend in 2001) led to a greater sense of urgency in the fossil utility industry to find earlier stage damage more reliably in seam welds. The AE studies mentioned provided proof of early stage detection of creep damage at the cavitation stage, often well before UT methods could reliably indicate a developing problem. Only the advanced metallographic method involving the use of cryo-cracking and SEM
examination at 2000-5000X was able to confirm this damage that AE was detecting at an early stage.

The standardization of the EPRI AE methodology for seam-welded piping began in earnest in January 2002 at the ASTM E07.04 acoustic emission subcommittee meeting. EPRI gave approval to the use of its documents and database as a necessary background for the development of the standard. The proposed standard WK 658 “Standard Test Method for Acoustic Emission Examination of Seam-Welded High Energy Piping” is nearing final balloting, and is expected to be approved in 2008. It is one of the most comprehensive and specific ever undertaken by an ASTM committee on an AE application.

Conclusions

Acoustic emission has proven its worth in online testing programs. Approximately 30% of lines tested have shown no significant findings of creep damage, and most others have shown only minor activity at suspect locations. The majority of seam-weld findings has been in elbows and bends, followed by hanger locations on horizontal line segments. These are known to be higher stressed areas, and offer further validation of the AE methodology. The correlation with follow-on nondestructive inspection has been very good, but the lesser sensitivity of UT inspection methods will generally not confirm early stage creep damage at the isolated cavitation stage. The economics of inspection and relative certainty of detection at an early stage of creep damage should be increasingly attractive to companies attempting to manage their piping systems in a climate of reduced capital and operations-maintenance spending.

References


