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FAILURE ANALYSIS CASE HISTORY

Failure analysis of superheater outlet header

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In November of 1998, the west superheater outlet header at an electricity generating plant began to leak steam. Subsequent investigation revealed the presence of a crack that extended for 360 degrees around the full circumference of the header and through the full cross-sectional thickness. The subsequent inspection of this header and the east superheater header revealed the presence of extremely severe ligament cracking. The resultant two segments of the header were held together by the remnants of several tube-to-header welds.

Thielsch Engineering was requested to inspect the west and the east superheater outlet headers. Both headers are essentially identical in design and operation. They are operated at a pressure of 2400 psi (16.5 MPa) and a temperature of 1005°F (540°C). They were both fabricated from seamless pipe produced in accordance with ASME Specification SA-335, which covers "Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service." The steel is Grade P22, a low-alloy steel with 2.25% chromium and 1% molybdenum. The pipe has an outside diameter of 16 in. (40 cm) and a nominal wall thickness of 3.5 in. (9 cm). The pipes have many rows of circumferential tube holes along their lengths (Fig. 1).

The purpose of the inspection was to determine the extent and severity of the cracking, to evaluate the feasibility of repair welding, and to establish the cause and origin of the cracking. The inspection, which included borescope and ultrasonic examinations, revealed the presence of severe circumferential cracking in both the west and east headers. The results of the failure analysis, which included several analytical techniques as well as a finite element analysis, confirmed that the failure was related to thermal fatigue.

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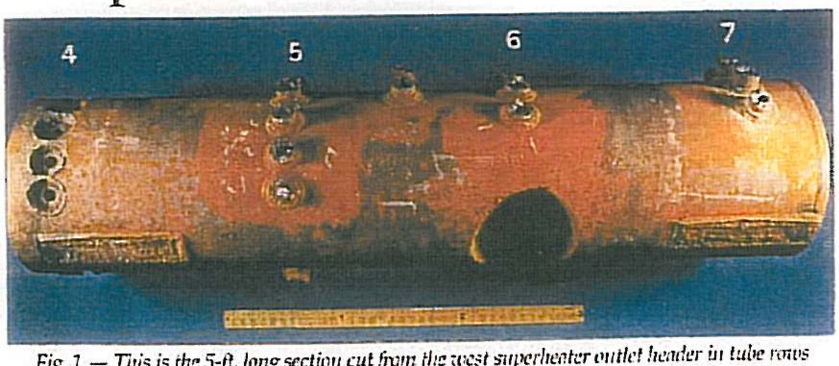

Fig. 1 — This is the 5-ft. long section cut from the west superheater outlet header in tube rows number 4 through 7. Subsegments of row 4 are referred to as A1, A2, A3, etc.

Analysis techniques

Various samples were removed from the header and were subjected to detailed metallurgical examinations. The samples were examined visually and then were subsectioned. The subsegments were analyzed to determine the material grade, the mechanical properties, and the mode of failure.

A 5-ft (1.5 m) section was cut from the west header (Fig. 1). This segment extended from tube row number 4 to tube row number 7. The visual examination confirmed that the crack that had caused the leak was located in tube row number 4. The crack essentially extended for 360 degrees around the circumference (Fig. 2), and for a large percentage of the circumference extended through the full cross-sectional wall thickness of the pipe (Fig. 3). The visual examination confirmed that the crack extended in a relatively straight manner through the cross-sectional thickness. In addition to the cracking in the ligaments, cracks had also developed in the toe of the lug weld that attached the header to a support.

After the visual examination was complete and any conditions of note had been documented photographically, the header section was further cut into subsegments. Visual examination of each of the mating fracture surfaces on segments A1 and A2 (from tube row 4) revealed ratchet marks, which are steps in the fracture surface formed when two cracks progressing at slightly different elevations ultimately meet. The presence of ratchet marks confirmed that multiple cracks had initiated in this tube row.

Visual examination of each of the fracture surfaces also revealed clam-

Fig. 2 — The circumferential through-wall crack in tube row number 4 is apparent along the inside surface of the header.

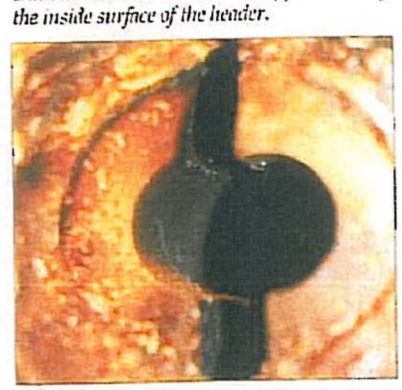

Fig. 3 — This circumferential crack extends through the wall thickness of the header.

shell marks or beach marks. Beach marks are formed as a crack starts to progress when stress is applied and removed in a cyclic manner. These marks are consistent with cracking produced by mechanical fatigue.

The location and orientation of the beach marks confirmed that, in each case, the cracking initiated at the corner formed by the intersection of the tube hole with the inside diameter surface of the header. The cracking then progressed through the ligament toward the adjacent tube hole, while at the same time progressing through the cross-sectional thickness of the header. In most cases, the crack extending from each adjacent tube hole met at the approximate midpoint of the ligament. This is typical of ligament cracking in superheater and reheater outlet headers produced by thermal fatigue.

Evaluation results

The results of this metallurgical evaluation confirmed that the header had been produced in accordance with the chemical composition and mechanical testing requirements of ASME Specification SA-335, Grade P22. No evidence was found of a material discrepancy that would have caused or contributed to the cracking.

The cracking in the west superheater outlet header was caused by thermal fatigue in conjunction with hoop stresses associated with the normal operation of the unit (Fig. 4). This type of cracking initiates at the corner formed by the intersection between the bore of the tube hole and the inside diameter surface of the header. The thermal gradient at this corner is higher than at any other location in the header. In addition, the mechanical stresses at this location are consistently higher than they are at any location within the cross-sectional thickness of the header. In time, if the stresses caused by the thermal gradients and the stresses associated with mechanical loads are sufficiently high and are cyclic in nature, these combined stresses will lead to initiation and progression of fatigue cracking.

The conclusion, that the cracking in the west superheater outlet header was caused by thermal fatigue, was confirmed by the results of the visual and metallurgical evaluations. The visual examination confirmed that the cracking initiated from the tube holes.

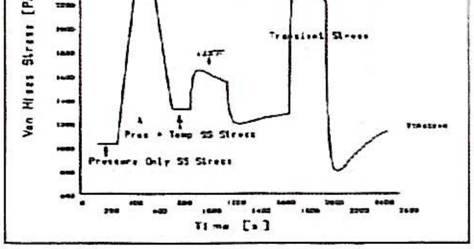

Fig. 4 — This graph illustrates the stress in the header model at point A.

Tube holes involve an extremely abrupt change in the cross-sectional thickness of the header, and as such, are subject to consistently higher mechanical and thermally-induced stresses than any other location within the header. Tube holes thus serve as a preferential site for cracking caused by thermal fatigue.

The visual examination also revealed that the cracking extended in a fairly straight manner across the width of the ligament, and through the cross-sectional thickness of the header. This is also consistent with cracking produced by thermal fatigue.

The metallurgical evaluation provided additional confirmation that the cracks extended in a fairly straight manner through the width of the ligaments, and through the cross-sectional thickness of the header. The crack progression mode was essentially transgranular. This, in conjunction with the relative straightness of the cracking, is consistent with fatigue.

The microstructures exhibited carbide spheroidization and agglomeration, particularly in the tempered bainite grains and at the grain boundaries. This is typical of piping and headers operating at temperatures of 1000°F (540°) and higher. Actual evidence of creep deterioration, including void formation, void linkage, and fissuring, was not apparent.

Cause of failure

It is considered likely, based on the fact that the most severe fatigue cracking was confined to approximately a 10 ft long (3 m) section, that some factor other than normal operation contributed to the fatigue cracking. Two explanations are plausible for the preferential nature of the cracking in the west superheater outlet header. The first explanation (which is considered to be the least likely) is that there is a low spot in the header. This low spot would permit condensate to collect when the boiler is brought off line. The condensate would flash to steam on start-up, exacerbating both the mechanical and thermally induced stresses. However, the inside diameter surface did not show evidence of this type of condition.

The second explanation (and the one considered to be most likely) involves periodic overheating of the header. The results of the finite element analysis of the header confirm that if the header is subject to a temperature fluctuation of 25°F (14°C), the stresses at the corner of the tube hole increase by 5% or 1100 psi (7.6 MPa). If the header is subject to a temperature fluctuation of 100°F (55°C), the stresses at the corner of the tube hole increase by 77% or 16,100 psi (110 MPa). If temperature fluctuations were routine, fatigue cracking would be expected to initiate and progress through the cross-sectional thickness of the header.

Metallurgical evidence indicates that the header has been subject to overheating periodically during the prior years of service. Specifically, a number of cracks were coated with extremely heavy oxide scale layers. The heaviest scale layer observed had a thickness of 0.017 in. (0.43 mm). At an operating temperature of 1005°F (540°C), this scale layer would have taken in excess of 300,000 hours to form. However, the boiler has been in service for only 120,000 hours. Thus, for this oxide scale layer to form, the header must have been subject to overheating. (At an operating temperature of 1105°F (595°C), this same scale layer could have formed in 30,000 hours.)

Scope of repair

The results of the failure analysis were utilized to determine the scope of repair, and the expected longevity of the repair. With the understanding that the header would be replaced after an additional 18 months of service, some ligament cracking was allowed to remain in place. The guillotine failure and the most severe ligament cracking were repaired successfully by a proprietary low stress welding technique. This allowed the header to be returned to service in less than a month.

The repair reduced very substantially the interruption of plant operations during a period of full capacity, an interruption that would have been much longer and far more costly if replacement headers had been required to be fabricated and installed. ■

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