Failure analysis of a primary reformer riser

Investigation revealed the root cause was creep rupture

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A primary reformer had experienced a hot spot on the north wall, about 3–4 m below the roof level. The plant was immediately shut down and an entire inspection of the reformer was conducted. Internal inspection revealed a crack on riser A, located about 3 m below the reformer roof. The crack developed on the north side of riser A against the north wall of the reformer. Accordingly, a failure analysis was requested to assess the failed riser condition, define the root cause and come up with corrective actions.

The reformer has been in service since 1987. It consists of eight rows. Each row contains 50 vertical catalyst tubes with a riser in the middle. Burners are fixed at the reformer roof. Feed goes through catalyst tubes coming from a header toward a manifold where the product is collected and flows up through risers out to a secondary reformer.

Risers operating conditions can be summarized as:

- Number of risers: eight
- Medium: HC + steam
- Flowrate: 139,971 kg/hr = 28,865 kg/hr HC + 111,106 kg/hr steam
- Riser inlet temperature: 799°C
- Riser outlet temperature: 832°C
- Riser inlet pressure: 35.15 kg/cm^2 g

FIG. 1. A longitudinal crack developed in riser A.

FIG. 2. Secondary cracks were observed.

FIG. 3. No cracks were observed in riser B.

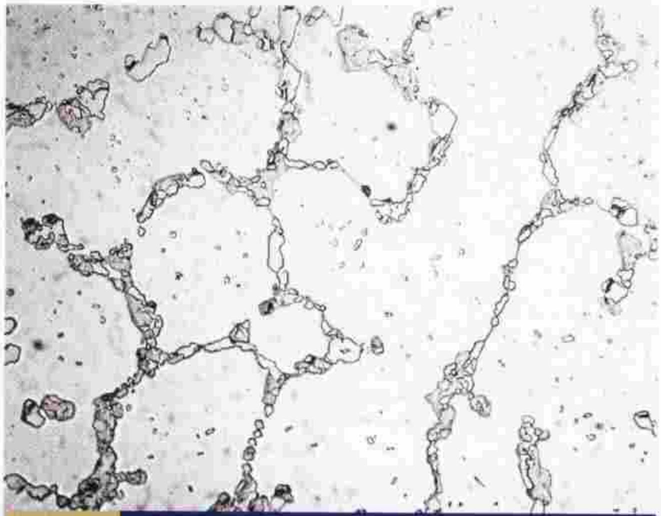

FIG. 4. Austenitic microstructure with carbides precipitating at grain boundaries within matrix (400X, etched).

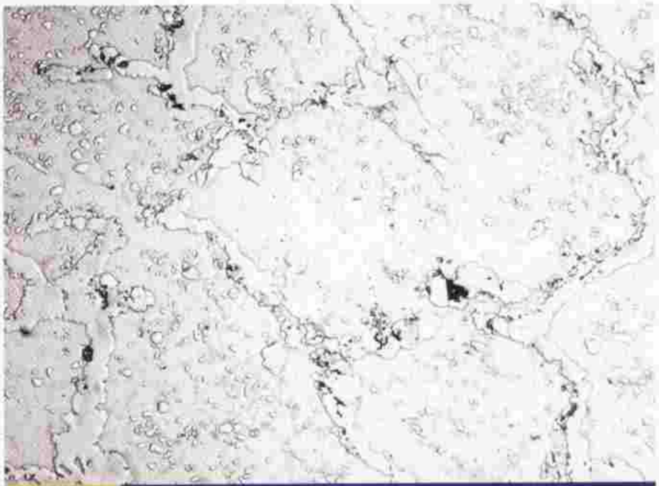

FIG. 5. Carbides coarsened and coalesced at grain boundaries. High concentration of secondary carbides precipitate inside the dendrites (400X, etched).

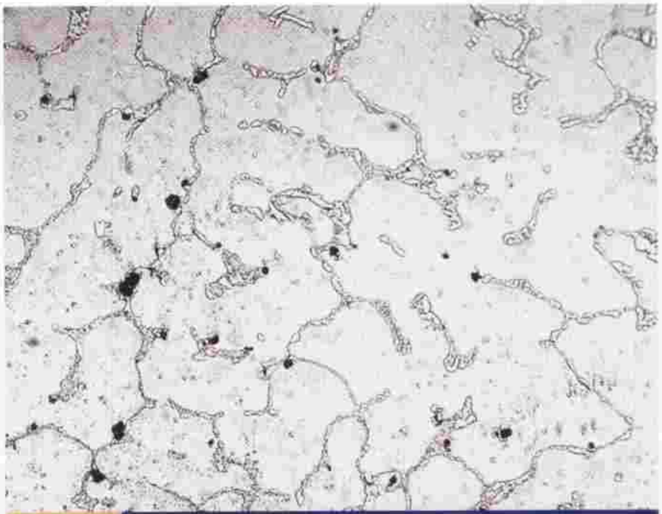

FIG. 7. Creep microvoids could be seen through the microstructure (200X, etched).

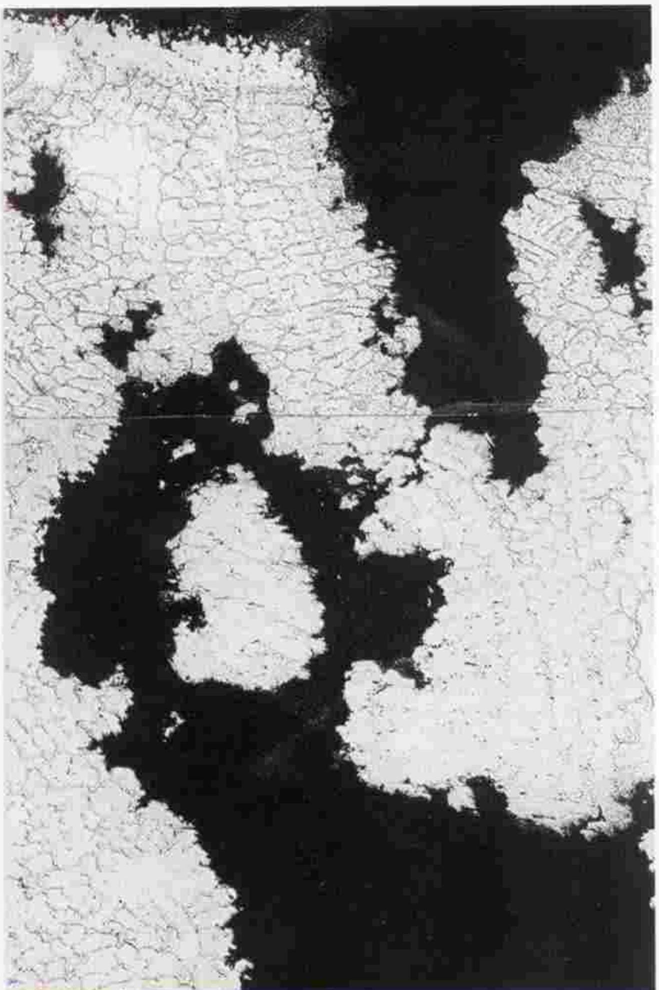

FIG. 6. Micrograph of one of the crack tips revealed the cause was creep rupture.

- Riser outlet pressure: 34.03 kg/cm^2 g
- Riser skin temperature: 890°C
- Material of construction: 25Cr-35Ni-Nb (cast).

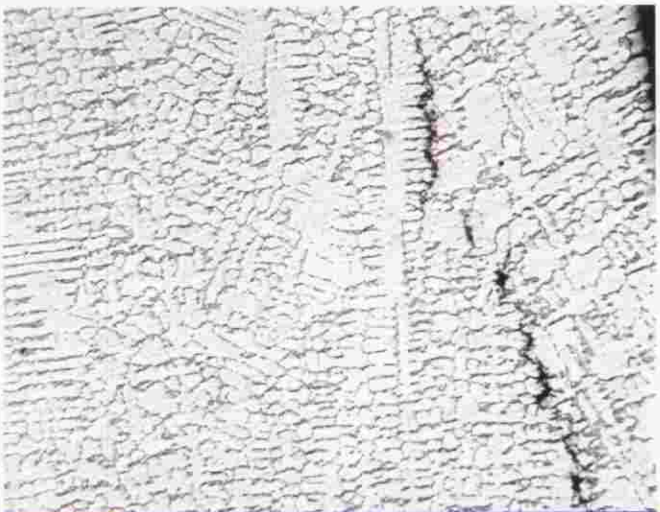

FIG. 8. Creep internal cracks were observed in some samples (50X, unetched).

Investigation. Two representative samples were submitted for analysis. One portion was taken from riser A, where the failure took place. The other piece was taken from riser B.

Visual inspection of the riser A sample revealed that a crack developed longitudinally (Fig. 1). Part of the crack was through the weld while the rest was through the base metal. Secondary cracks associated with the main crack were observed as well (Fig. 2). Some plastic deformation in the form of bulging had been noticed, especially in regions around cracks. The material was nonmagnetic.

As Fig. 3 shows, no signs of cracks or bulging were observed on the riser B sample. The weld seemed intact and in sound condition, yet the material was not magnetic. Not much wall loss had been observed in both samples.

Six samples were prepared for metallography from riser A. Three were selected from the cracked area, i.e., crack tips. The rest were selected from regions away from the crack. Four samples were cut from the riser B portion, two from the welding area and the other two from base metal.

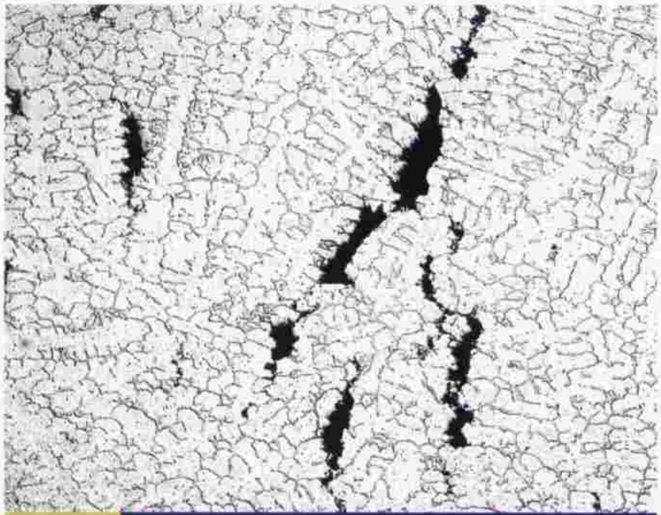

FIG. 9. Minor creep ruptures were noticed within the material of both risers (50X, unetched).

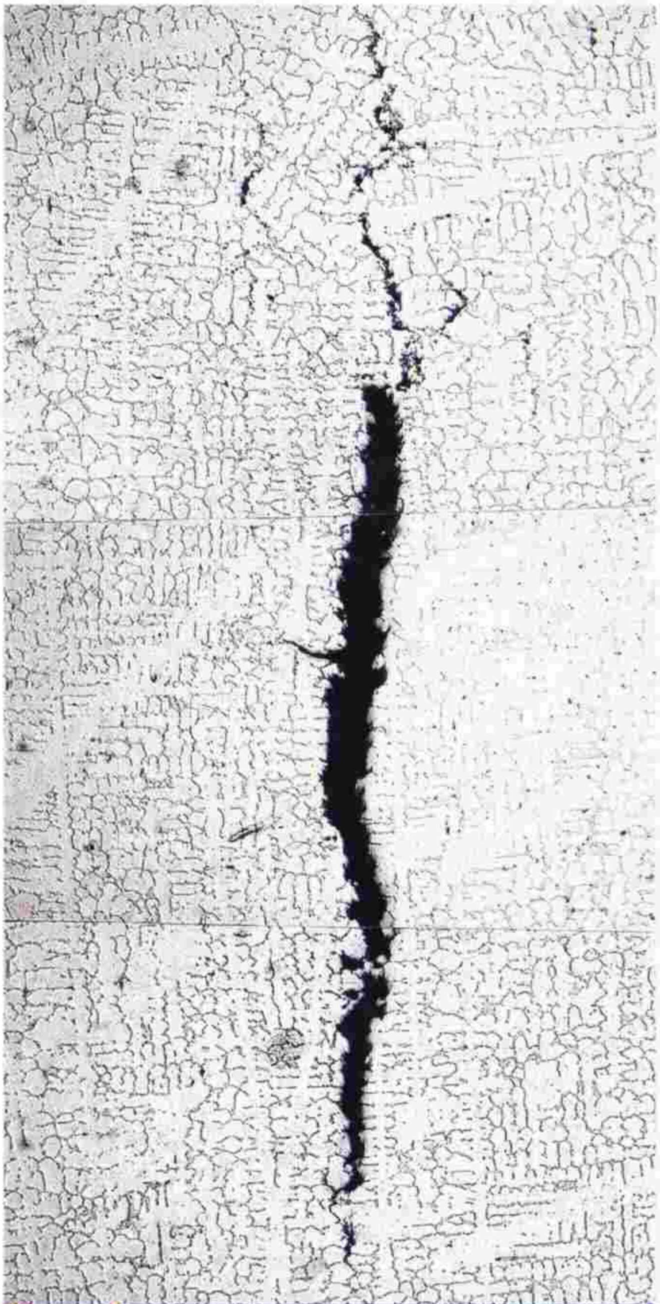

FIG. 10. A crack developed through the riser wall. Creep voids linked up and oriented to form such a crack (50X, unetched).

Optical microscopy revealed austenite microstructure with carbides, coalesced and coarsened, precipitating at grain boundaries. Additionally, secondary carbides were observed within matrices (Figs. 4 and 5). Fig. 6 discloses the nature of the crack. This photomicrograph confirms that the crack was caused by creep rupture. Almost all sample microstructures had microvoids and stress ruptures in different stages (Figs.7–10). Some microvoids had oriented and linked up, constituting internal and external cracks.

As for riser B welding, which visually looked sound, a high concentration of microvoids was found. The weld microstructure was austenitic-rich with carbides (Figs. 11 and 12).

Micro-hardness testing was conducted for the riser materials in different locations. Base metal hardness ranged from 267 Hv to 305 Hv, whereas welding hardness was about 296 Hv. The tabulated hardness value is typically 185 Hv. Material chemical analysis, using spectroscopy, gave an almost typical composition of 25 Cr-35 Ni+Nb alloy.

Discussion. Creep, per its definition, causes the material to undergo time-dependent plastic deformation that leads to changes in component dimensions (e.g., bulging). Creep rupture usually involves secondary cracks associated with the main crack.

The creep process usually involves three distinct stages. The first, called primary creep, is the region in which the material initially undergoes elastic strain produced by the applied load. Still within the same region, increasing plastic strain at a decreasing strain rate comes after the initial elastic strain. Following primary creep is the secondary creep stage, where the creep rate is constant at a minimum rate. Design life of a heat-resistant alloy can be estimated based on the length of the secondary creep period. The material experiences plastic deformation but the recovery process continues in this stage.

The tertiary creep stage is the region in which the strain rate drastically increases with rapid extension to fracture. When the material that undergoes creep approaches the tertiary region, rounded microvoids start nucleating through the material microstructure. As time goes on, some microvoids start aligning and link up, forming creep minor cracks and ruptures. Since this is the situation of the current case, risers A and B experienced final-stage creep, in which the material is not valid to be used.

As indicated from the material data sheet, design life of risers is 100,000 hr (about 11.5 yr). However, the risers had been in service for about 140,000 hr (16 yr). Fig. 13 illustrates the influence of time as well as temperature on the minimum stress value needed to produce rupture. Obviously, as temperature, exposure time or both increase, minimum stress to produce rupture decreases. For instance, after 1,000 hr of exposure to 870°C service, minimum stress to produce rupture is about 47 MPa.

However, at the same temperature and after 100,000 hr of exposure, minimum stress to produce rupture is about 25 MPa. So as exposure time approaches 140,000 hr, minimum stress to

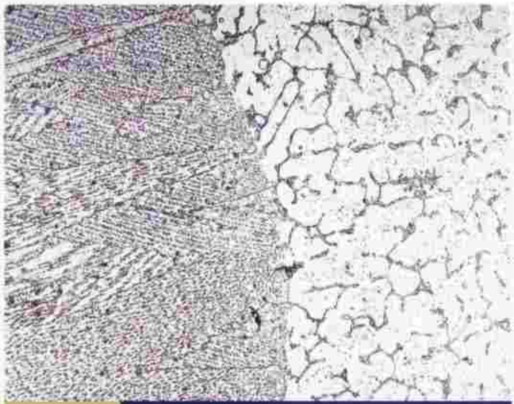

FIG. 11. Carbides-rich austenitic weld microstructure (100X, etched).

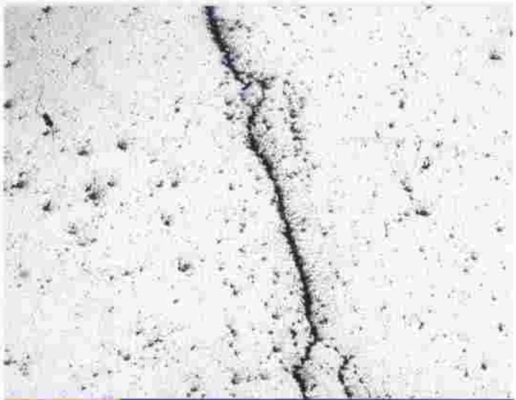

FIG. 12. Creep voids and cracking were observed in the weld (50X, unetched).

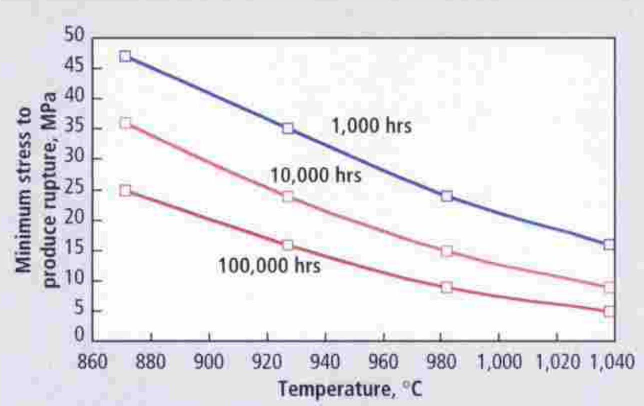

FIG. 13. Both time and temperature influence the minimum stress value to produce rupture.

produce rupture is expected to be considerably below 25 MPa and whether the material can still withstand process loads is in doubt. It should be emphasized that these data are obtained from controlled ideal laboratory experiments. However, it is very difficult to determine the exact design life of reformer furnace tubes.

Alloy mechanical properties change as a function of time and temperature. This change of mechanical properties is attributed to the change in material microstructure. Most heat-resistant alloys rely on carbide precipitation to provide adequate creep strength. However, an optimum size of carbides qualifies the material to exhibit good creep resistance without adversely affecting the material mechanical properties significantly. Virgin 25 Cr-35 Ni alloy microstructure would show presence of stringers that shape primary carbides precipitating at grain boundaries.

Once the alloy is subjected to the service temperature, primary carbides start to convert to more stable carbides called secondary carbides. As time goes on, more secondary carbides precipitate at grain boundaries and within the matrix. Grain boundary carbides start coarsening and coalescing as a result of long exposure to high-temperature service, leading to a significant decrease in the alloy mechanical properties. This process takes a relatively long time, about the design life, to fully degrade material performance, and the material is considered aged.

Precipitation and crystallization of a high amount of carbides will induce internal stresses within the material. As they grow at grain boundaries (carbides coalesced and coarsened), brittle fracture will occur through the carbide layer and grain boundaries. In fact, carbides accumulation leads to loss of ductility and toughness. The material thermal expansion becomes very low.

Riser material 25 Cr-35 Ni+Nb is considered one of the most common alloys used in reformer furnace applications. Niobium addition improves stress rupture strength through formation of niobium carbides that are more stable at higher temperatures. Also, presence of niobium improves carburization resistance, but lowers ductility.

Recommendations.

- All risers must be immediately replaced with new material of the same type as the original one. The existing material cannot be guaranteed to handle process loads as it ages.
- Catalyst tube replacement should be considered with risers replacement.
- The reformer owner should have conducted a thorough tube life assessment immediately after they passed their design life (i.e., 100,000 hr).

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