Materials safety: article exercise

You are working as a materials expert in your organization and your responsibility is to guarantee safe and efficient use of materials in your facility. One day, a failure in similar facility is brought to your attention, and you need to investigate the possible implications this failure has for your facility. Your job is to interpret and analyze the given failure report and to write a report, which will allow others in your organization to understand the key developments and causes leading to the failure and the necessary actions for prevention of such failures.

Read the given article and analyze the failure. Describe, how the deformation and failure mechanisms presented during the course are reflected in the case and establish the chain of actions leading to the failure. The report should work as an introductory material to your team; it should not be very long but it should enable other team members to understand the key features of the failure without reading the failure report itself.

In addition to establishing the primary cause of the failure, show why alternate failure mechanisms can be ruled out. Some failure mechanisms have not been discussed in the course yet. Conduct the analysis using your present knowledge on the subject.

If the author of the failure analysis has, in your view, neglected to address some aspects of the failure, you may indicate this in your report and suggest tests or actions that should have been done to clarify the issue.

Prepare your response by editing this word document and export it as PDF. The file name identifies you and the article. Do not change the file name (other than the extension to pdf). E-mail the pdf to "materials.safety@iikka.fi".

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You may use the question list below to guide you in your analysis:

A. Description of investigation methods applied

- What means of investigation were used in the failure analysis?
- What computational methods were used?
- What material or results were obtained?

B. The primary cause of the failure and description of the failure mechanism

- What is the primary cause of the failure (also provide reasoning)?
- What's the chain of action that led to the failure?

C. Ruling out alternate failure mechanisms

- Can plastic deformation be ruled out? If yes, explain how.
- Can creep be ruled out? If yes, explain how.
- Can brittle fracture be ruled out? If yes, explain how.
- Can fatigue be ruled out? If yes, explain how.
- Can environmentally assisted failure be ruled out? If yes, explain how.

D. Recommendations to prevent similar failures in the future

- How should the design, material, use, etc. be develop to avoid similar failures in the future? Provide several alternatives and indicate most promising.

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Materials Safety analysis report on creep failure of superheater tubes

Problem Overview:

The report investigated the reasons why certain superheater tubes kept failing over time. They observed a recurring "fish-mouth" type of rupture in these tubes, especially in the curved areas. By examining the tubes' structure and materials, they aimed to uncover the causes of these failures. Their insights offer guidance for future design improvements to ensure safer and more efficient heating systems and to reduce maintenance time interval and costs.

A. Description of investigation methods applied

- **What means of investigation were used in the failure analysis?**

The author tries to determine whether creep and environmentally induced factors are associated with the fish-mouth shaped failures observed in superheater tubes. From the report, the means of investigation for the failure analysis included:

1. **Macroscopic observations**: The author used a Leica MS 5 and a Nikon SMZ 1500 stereomicroscope to perform macroscopic observations of the failed tubes.
2. **Microscopic observations**: An FEI XL40 SFEG scanning electron microscope (SEM) equipped with an electron dispersive spectrometry X-ray microanalysis system (EDAX) was utilized for microscopic observations.
3. **Metallographic examination**: A Nikon Epiphot 300 inverted metallurgical microscope was used for metallographic examination. Before this examination, cross-sections of the failed tubes were prepared using hot-mounting, wet grinding up to 1200 grit SiC paper, and polishing with diamond and silica suspensions.
4. **Chemical etching**: The specimens were chemically etched by immersion in a Nital reagent (2% HNO_3 ethanol solution) for 10 seconds. This was followed by cleaning with ethanol and drying with a hot-air streams

- **What computational methods were used?**

The author lists a couple of computation methods as follows:

1. **Optical Micrographs**: These provide detailed images of the material's structure, allowing for a closer look at the grain boundaries, voids, and other microstructural features. For instance, the paper shows optical micrographs of the failed-tube wall
2. **SEM (Scanning Electron Microscopy) Images**: SEM records high-resolution images of the material's surface. The report contains several SEM images, such as those revealing the material's recrystallization and the initial structure of the Cr-containing steel grade
3. **Stereographs**: These are used to provide a three-dimensional view of the material's structure. The paper references a stereograph of a cross-section perpendicular to the circumferential weldment, showing values of the Vickers hardness measurements.
4. **Vickers hardness measurements**: The paper mentions the use of Vickers hardness measurements to determine the material's hardness at specific areas, especially in the vicinity of weldments.

- **What material or results were obtained?**

Main result: Failure is identified at the curved areas of the pipeline

The failed parts exhibited a "fish-mouth" thin-lip rupture, commonly observed in creep-induced failures of superheater and reformer tubes. Rupture always occurred at the inner wall of the tube, with the wall thickness at the tip diminishing from the original 6 mm to about 1 mm. Failed parts from areas near circumferential weldments exhibited a "cobra" appearance.

Material Identification: The tube material was identified as a low-alloy ferritic steel, likely corresponding to the 15Mo3 grade. This identification was based on metallographic observation and EDAX microanalysis.

B. The primary cause of the failure and description of the failure mechanism

- **What is the primary cause of the failure (also provide reasoning)?**

The primary cause of the failure is likely to be creep-induced failure. There are four main reasons for this type of failure:
- The failed parts displayed a "fish-mouth" thin-lip rupture, which is commonly observed in cases of creep-induced failure of superheater and reformer tubes.
- Precipitates at the grain boundaries indicated cementite spheroidization, resulting from the prolonged heating during operation. This can accelerate creep behavior.
- Different stages of creep void evolution on the same tube cross-section (initiation, growth, and coalescence) suggest a temperature gradient across the tube wall, which can enhance creep deformation and eventual failure.
- Failed parts near circumferential weldments displayed a "cobra" appearance. Welded areas are susceptible to creep-induced failure due to residual stresses and microstructural changes between the two alloys from the welding process.

- **What's the chain of action that led to the failure?**

The chronological order of the superheater tubes’ failure is as follows:

1. Prolonged heating and material transformation: The tube underwent prolonged heating during operation. This led to cementite spheroidization, a material transformation observed at the grain boundaries.
2. Temperature gradient across the tube wall: This gradient led to the co-existence of different stages of creep void evolution on the same tube cross-section, including initiation, growth, and coalescence of voids.
3. Failure near welding seams: fracture cracks initiating near the seam and propagating within one of the joined tubes, almost parallel to the main axis.
4. Systematic Recording of Failures: data recorded over one year of the pipeline's service showed that material failures occurred on average every 15 days. These failures were localized either at curved areas of the tubes or near circumferential weldments.

C. Ruling out alternate failure mechanisms

- Can plastic deformation be ruled out? If yes, explain how.

The paper mentions the observation of "metal plastic flow striations" along the tube axis, especially in the curved areas of the pipeline. This suggests that there was some form of plastic deformation prior to failure. However, this plastic flow is probably a result from the creep mechanism rather than conventional plastic deformation. So plastic deformation as the main failure mechanisms can be ruled out.

- Can creep be ruled out? If yes, explain how.

Creep cannot be ruled out since this is one of the main failure reasons stated in the paper

- Can brittle fracture be ruled out? If yes, explain how.

Brittle fracture can be ruled out since the material deformation is observed to be quite ductile (void nucleation, growth, and coalescence).

- Can fatigue be ruled out? If yes, explain how.

Fatigue cannot be ruled out. The superheater tubes operate under high temperatures and pressures, conditions that are conducive to creep. However, the frequent interruptions for maintenance and potential alternations in steam pressure could introduce cyclic thermal stresses, which are a sign of fatigue. Therefore, fatigue should be considered in this report as well.

- Can environmentally assisted failure be ruled out? If yes, explain how.

Environmentally assisted failure cannot be ruled out since this is one of the main failure reasons stated in the paper, such as temperature gradient and material phase transformation.

D. Recommendations to prevent similar failures in the future

- How should the design, material, use, etc. be developed to avoid similar failures in the future? Provide several alternatives and indicate the most promising.

To avoid similar failures in the future, several design, material, and usage recommendations can be inferred from the paper:

1. Material selection: As the calorific value of lignite seems to increase with exploitation depth, the 13Mo3 steel grade should be rejected. Instead, more heat-resistant steel grades should be considered as materials of choice to withstand the high temperatures and stresses experienced in such environments.

2. Improved welding techniques: given that some failures were observed near welding seams, it might be beneficial to explore improved welding techniques or materials that can better withstand the operating conditions of superheater tubes.

3. Monitoring and maintenance: regular monitoring of the pipeline's condition and performance can help detect early signs of potential failures. This includes checking for signs of creep, material transformation, and other microstructure anomalies.