3.23 Creep and Stress Rupture

3.23.1 Description of Damage

a) At high temperatures [typically greater than half the absolute melting temperature in °R (°K)], metal components can continuously deform under load, even below their elastic yield stress. This time-dependent deformation of stressed components is known as creep.

b) Exposure to stress at high temperatures initially promotes void formation at grain boundary triple points, which with time grow to form fissures and, later, cracks.

c) As fissures and cracks coalesce, failure can occur, although the gross deformation associated with tensile overloading is not observed.

3.23.2 Affected Materials

All metals and alloys.

3.23.3 Critical Factors

a) The rate of creep deformation (creep rate or strain rate) is a function of the material, applied stress, and temperature.

   1. Creep rate is very sensitive to relatively small changes in temperature or stress. Generally, a temperature increase of about 25 °F (15 °C) or a 15 % increase in stress can cut the remaining life in half, or worse, depending on the alloy.

b) Table 3-23-1 lists threshold temperatures for different metals above which creep damage is a concern. If the metal temperature exceeds these values, creep deformation and creep cracking can eventually occur.

c) The creep life of metal components becomes extremely long at temperatures below their threshold in Table 3-23-1, even at the high stresses near a crack tip.

d) Creep deformation is the result of relative movement between individual (microscopic size) grains or other discontinuities within the metal. As creep progresses and cracks develop and grow from microscopic size to macroscopic size, the cracks eventually grow through the wall resulting in failure, at which point they are clearly visible.

   1. Because a coarse-grained material has less grain boundary surface area than a fine-grained material, a material heat treated to have a coarse-grained structure will generally have better creep strength than the same material with a fine-grained structure.

e) Creep cracking, once initiated, can progress rapidly.

f) Increased stress due to loss in thickness from corrosion will reduce time to creep failure.

g) The appearance of creep cracking with little or no apparent deformation usually indicates that the material has low creep ductility. Low creep ductility is:

   1. more pronounced in higher tensile strength materials and welds,

   2. more prevalent at lower temperatures in the creep range or with low stresses at the upper temperatures in the creep range,

   3. more likely in a coarse-grained material than in a fine-grained material,

   4. not evidenced by a deterioration of ambient temperature properties, and

   5. promoted by certain carbide types in some Cr-Mo steels.

3.23.4 Affected Units or Equipment

a) Creep damage is found in high-temperature equipment operating in the creep temperature range. Heater tubes in fired heaters, as well as tube supports, hangers, and other furnace internals, as well as high-pressure steam tubes in boilers, can be susceptible to creep.

b) Hot-wall catalytic reforming reactors, reactor piping, furnace tubes, hydrogen-reforming furnace tubes, hot-wall FCC reactors, and FCC main fractionator and regenerator internals all operate in or near the creep temperature range.

c) Low creep ductility failures have occurred in weld HAZs at nozzles and other high-stress areas in 1¼Cr-½Mo catalytic reformer reactors. Cracking has also been found at long seam welds in some high-temperature 1¼Cr-½Mo piping and reactors in catalytic reformers, primarily due to "peaking" of the long-seam welds.

d) Welds joining dissimilar materials (e.g. ferritic to austenitic welds) may suffer creep-related damage at high temperatures due to differential thermal expansion stresses.

3.23.5 Appearance or Morphology of Damage

a) The initial stages of creep damage can only be identified by scanning electron microscope (SEM) metallography. Creep voids typically show up at the grain boundaries. At later stages, they grow into microfissures and then cracks. When the fissures run the entire length of a grain boundary, they can be seen by standard optical microscope metallography, although they will not necessarily be easy to find.

b) At temperatures well above the threshold limit, noticeable deformation may be observed. For example, heater tubes may suffer long-term creep damage and exhibit significant, measurable bulging before rupture occurs. The amount of deformation before fracture is highly dependent on the material and the combination of temperature and stress level. (Figure 3-23-1 to Figure 3-23-3)

c) In vessels and piping, creep cracking can occur where high metal temperatures and stress concentrations occur together, such as near major structural discontinuities including pipe tee joints and vessel nozzles, as well as at weld flaws.

3.23.6 Prevention/Mitigation

a) There is little that inspectors or operators can do to prevent this damage once a susceptible material has been placed into creep service, other than to minimize the metal temperature, particularly with fired heater tubes. Avoiding stress concentrations is important during design and fabrication.

b) Low creep ductility can be minimized by the careful selection and specification of materials. See SRC (3.54).

c) Creep damage is not reversible. Once damage or cracking is able to be detected, much of the life of the component has been used up, and typically the options are to repair or replace the damaged component. Higher PWHT in some cases can produce a more creep ductile material with longer life.

    1. Equipment—Repair of creep damaged catalytic reformer reactor nozzles has been successfully accomplished by grinding out the affected area (making sure all the damaged metal is removed), re-welding, and careful blend grinding to help minimize stress concentration. PWHT temperatures must be carefully selected and may require a higher PWHT than originally specified.

    2. Fired Heater Tubes—Alloys with improved creep resistance may be required for longer life. Heaters should be designed and operated to minimize hot spots and localized overheating, e.g. due to flame impingement or improper burner operation. (Figure 3-23-3) Minimizing process-side fouling and deposits and fire-side deposits and scaling, both of which can necessitate overfiring to maintain process temperatures, can maximize tube life.

    3. Remaining life of heater tubes can be assessed in accordance with API 579-1/ASME FFS-1.

4. Retirement criteria based on diametric growth and loss of wall thickness are highly dependent on the tube material and the specific operating conditions. Different retirement strategies may be needed for different situations.

3.23.7 Inspection and Monitoring

a) Creep deformation and the associated microvoid formation, fissuring, and dimensional change are not effectively found by any one inspection technique. A combination of proper NDE techniques (surface and volumetric), dimensional measurements, and field metallographic replication (FMR) are often needed. Destructive sampling and metallographic examination are generally used to confirm damage.

   1. Conventional NDT methods, e.g. WFMT, VT, PT, or UT techniques, are not able to detect creep damage prior to the formation of a creep crack.

   2. FMR is typically used where evidence has been found through other inspection methods.

   NOTE FMR performed on the surface of a component will not show subsurface damage and will miss internal creep fissuring.

b) For pressure vessels, inspection is generally focused on welds of Cr-Mo alloys operating in the creep range. The choice of NDE methods may depend on the severity of any apparent damage. On the viewable surface, VT is generally performed, followed up with PT or WFMT. For subsurface examination for cracking or gross fissuring, angle beam UT (SWUT or PAUT) or other high-resolution NDE methods, such as TOFD, can also be employed, although the early stages of creep damage are very difficult to detect.

c) Fired heater tubes are typically inspected for evidence of overheating, bulging, corrosion, and erosion as follows.

   1. Tubes can be VT examined for bulging, blistering, cracking, sagging, bowing, or rubbing wear. VT will not detect internal creep damage but is used to identify areas where further NDE may be needed.

   2. UT wall thickness measurements of selected heater tubes can be made where wall losses are most likely to occur. UT thickness measurements will not detect creep damage but are used for creep examination to identify areas where further NDE may be needed.

   3. Tubes can be examined for evidence of diametric growth due to creep with a strap or go/no go gauge. Dimensional inspection will not detect internal creep damage but will detect large, apparent creep deformation and also identify areas where further NDE may be needed.

   4. In-line inspection (smart pigging) of heater tubes will provide a more complete assessment of remaining wall thickness and diameter growth. However, it is unlikely to detect internal creep damage, and further NDE may be needed.

   5. Automated inspection devices (crawlers) are commercially available for inspecting hydrogen reformer heater tubes. The selection of such equipment for inspection, as well as analysis and interpretation of results, involves careful evaluation.

3.23.8 Related Mechanisms

Short-term overheating—stress rupture (3.55), SRC (3.54), and dissimilar metal weld (DMW) cracking (3.26).

3.23.9 References

1. API 579-1/ASME FFS-1, *Fitness-For-Service*, American Petroleum Institute, Washington, DC.

2. API Standard 530, *Calculation of Heater-tube Thickness in Petroleum Refineries*, American Petroleum Institute, Washington, DC.

3. API Standard 660, *Shell-and-Tube Heat Exchangers*, American Petroleum Institute, Washington, DC.

Table 3-23-1—Threshold Temperatures for Creep (Reference 1)

Material	Temperature Limit
Carbon steel [UTS > 414 MPa (60 ksi)]	650 °F (345 °C)
Carbon steel [UTS > 414 MPa (60 ksi)]	700 °F (370 °C)
Carbon steel—Graphitized	700 °F (370 °C)
C-½Mo	750 °F (400 °C)
1¼Cr-½Mo—Normalized and tempered	800 °F (425 °C)
1¼Cr-½Mo—Annealed	800 °F (425 °C)
2¼Cr-1Mo—Normalized and tempered	800 °F (425 °C)
2¼Cr-1Mo—Annealed	800 °F (425 °C)
2¼Cr-1Mo—Quenched and tempered	800 °F (425 °C)
2¼Cr-1Mo-V	825 °F (440 °C)
3Cr-1Mo-V	825 °F (440 °C)
5Cr-½Mo	800 °F (425 °C)
7Cr-½Mo	800 °F (425 °C)
9Cr-1Mo	800 °F (425 °C)
9Cr-1Mo-V	850 °F (455 °C)
12 Cr	900 °F (480 °C)
AISI Type 304 and 304H	950 °F (510 °C)
AISI Type 316 and 316H	1000 °F (540 °C)
AISI Type 321	1000 °F (540 °C)
AISI Type 321H	1000 °F (540 °C)
AISI Type 347	1000 °F (540 °C)
AISI Type 347H	1000 °F (540 °C)
Alloy 800	1050 °F (565 °C)
Alloy 800H	1050 °F (565 °C)
Alloy 800HT	1050 °F (565 °C)
HK-40	1200 °F (650 °C)

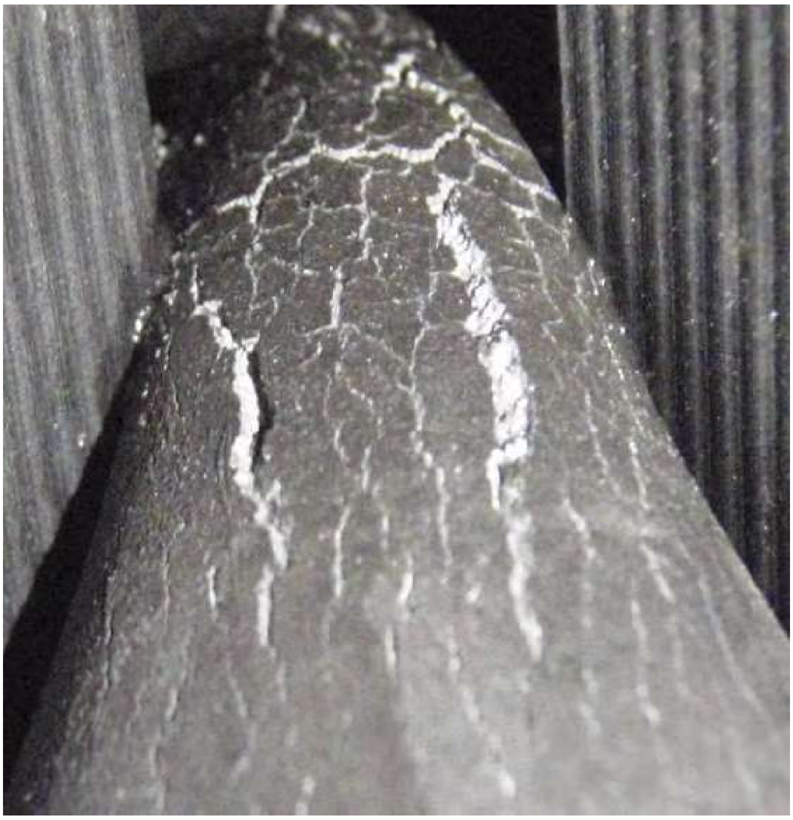
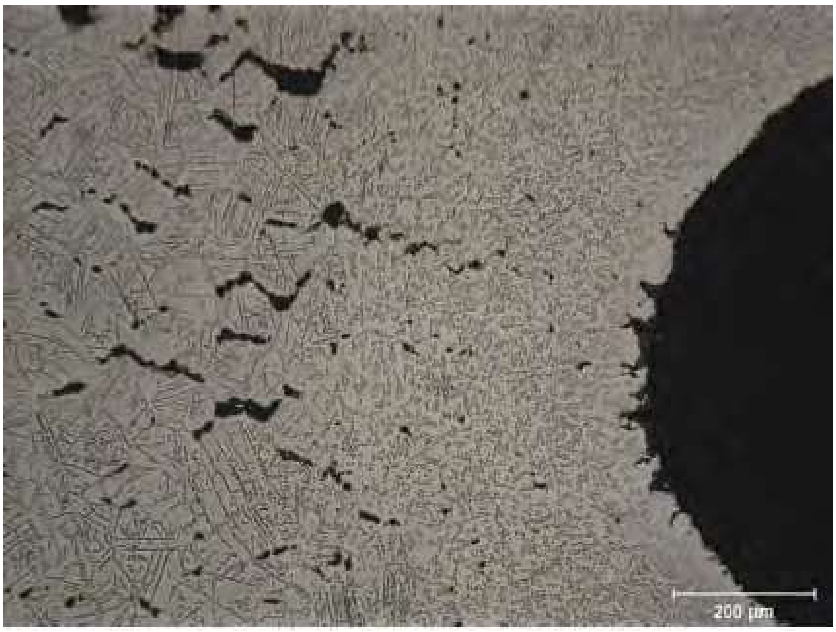


Figure 3-23-1—A pinched Alloy 800H pigtail with opened-up creep fissures on the surface.

Figure 3-23-2—Creep rupture of an HK40 heater tube.

(a)



(b)

Figure 3-23-3—Creep failure of Type 310 SS heater tube guide bolt after approximately 7 years of service at 1400 °F (760 °C). (a) Cross section at 10X magnification, as-polished. (b) Voids and intergranular separation characteristic of long-term creep (magnification 100X, etched).