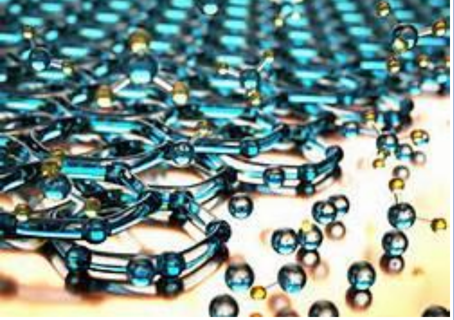



Materials Science

Lecture 19

Lebanese University - Faculty of Engineering – Branch 3

Fall 2022

Dr. Ali HARKOUS

Contents

Lecture 19:

Chap6: Failure

6.9. Crack Initiation and Propagation

- The **process of fatigue** failure is characterized by **three distinct steps**:

1. **Crack initiation**, in which a **small crack forms** at some point of **high stress** concentration;
2. **Crack propagation**, during which this **crack advances** incrementally **with each stress cycle**;
3. **Final failure**, which occurs **very rapidly** once the advancing crack has reached a **critical size**.

- **Cracks** associated with fatigue failure **almost** always **initiate** (or nucleate) on the **surface** of a component at some **point of stress concentration**.

- **Crack nucleation** sites include surface **scratches, sharp fillets, keyways, threads, dents,** and the like.

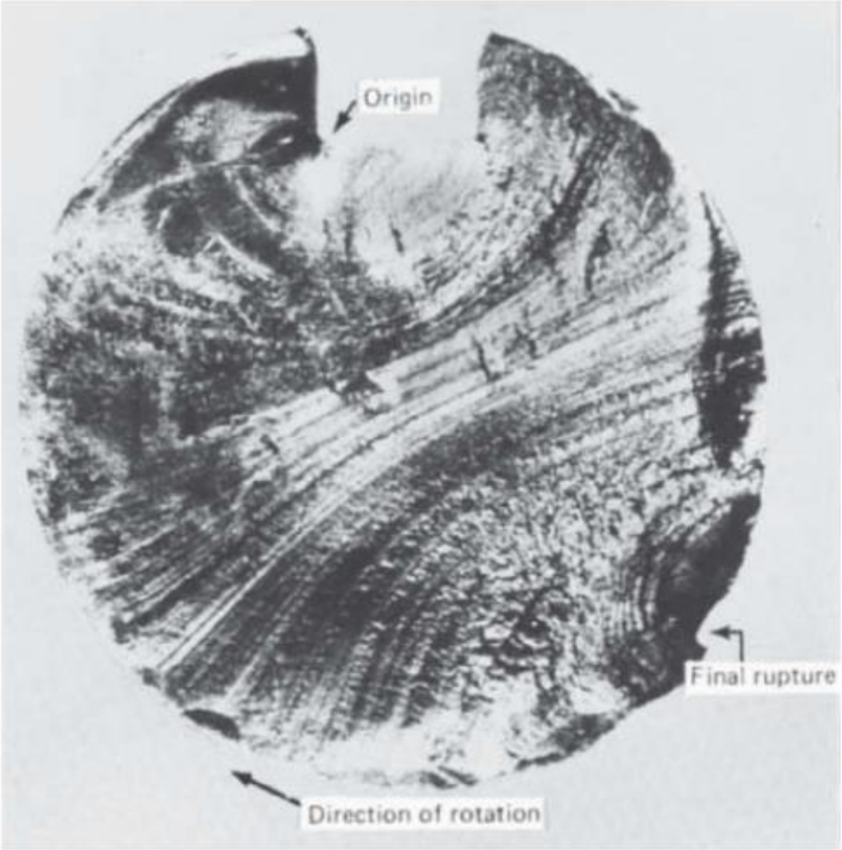
- In addition, **cyclic loading can produce microscopic** surface **discontinuities** resulting from **dislocation slip** steps that may also act as **stress raisers** and therefore as **crack initiation** sites.

6.9. Crack Initiation and Propagation

- The **region** of a fracture surface that **formed** during the crack **propagation** step may be **characterized** by **two types** of markings termed **beachmarks and striations.**

- **Both** features **indicate** the **position** of the **crack tip** at **some point** in time and appear as concentric **ridges** that **expand away** from the crack initiation site(s), **frequently** in a **circular** or **semicircular pattern**.

- **Beachmarks** (sometimes also called **clamshell marks**) are of **macroscopic** dimensions (Figure), and may be observed with the **unaided eye**.

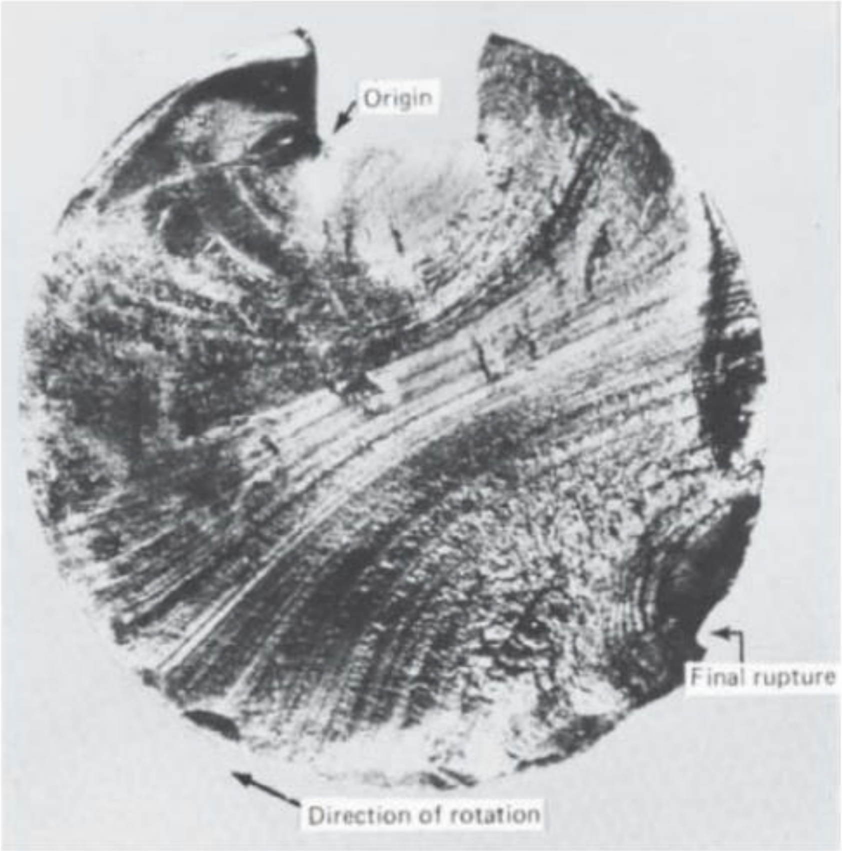


Fracture surface of a rotating steel shaft that experienced fatigue failure. Beachmark ridges are visible in the photograph.

6.9. Crack Initiation and Propagation

- These **markings** are **found** for components that experienced **interruptions during** the crack **propagation** stage—**for example**, a **machine** that operated **only during normal workshift hours**.

- Each **beachmark** band **represents** a **period** of **time** over which **crack growth occurred**.



Fracture surface of a rotating steel shaft that experienced fatigue failure. Beachmark ridges are visible in the photograph.

6.9. Crack Initiation and Propagation

- However, fatigue **striations** are **microscopic** in size and subject to **observation** with the electron **microscope** (either **TEM** or **SEM**).
- The **figure** is an **electron fractograph** that shows this feature.
- **Each striation** is thought to represent the **advance distance** of a crack **front during** a **single load cycle**.
- Striation width **depends on**, and **increases** with, **increasing stress range**.
- **During the propagation of fatigue cracks** and on a microscopic scale, there is **very localized plastic deformation** at **crack tips**, **even though** the **maximum applied stress** to which the object is exposed in each stress cycle lies **below** the **yield strength** of the metal.

Transmission electron fractograph showing fatigue striations in aluminum. 9000X.

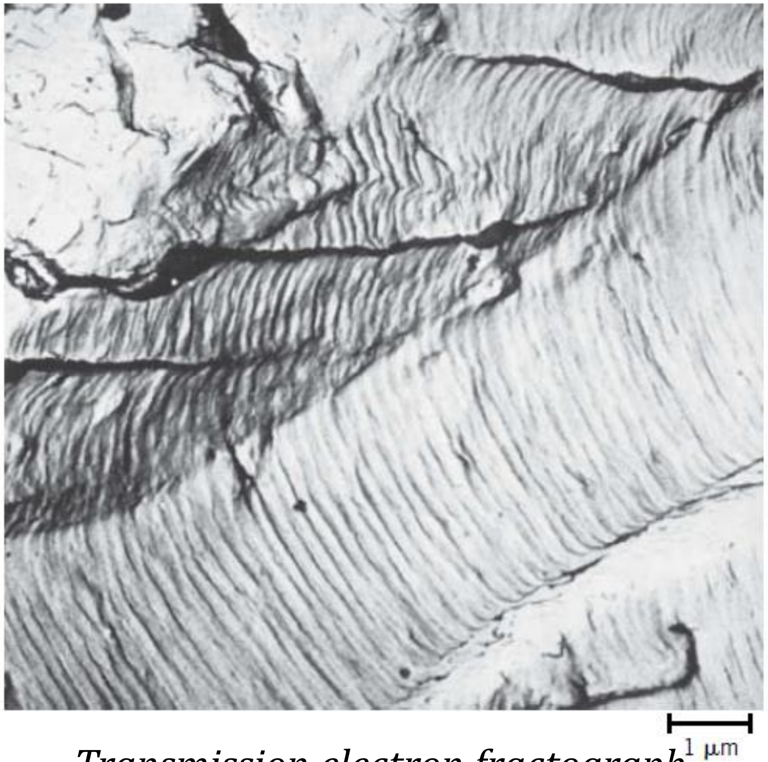
6.9. Crack Initiation and Propagation

- This **applied stress** is **amplified** at **crack tips** to the degree that **local stress levels exceed** the **yield strength**.

- The **geometry** of fatigue **striations** is a **manifestation** of this **plastic deformation**.

- It should be emphasized that although both **beachmarks and striations** are fatigue fracture surface features having **similar appearances**, they are nevertheless **different** in both **origin** and **size**.

- There may be **thousands of striations** within a **single beachmark**.



Transmission electron fractograph showing fatigue striations in aluminum. 9000X.

6.9. Crack Initiation and Propagation

- Often the **cause of failure** may be **deduced after examination** of the failure **surfaces**.

- The presence of **beachmarks and/or striations** on a fracture surface **confirms** that the **cause** of failure was **fatigue**.

- Nevertheless, the **<u>absence</u> of either or both does not exclude fatigue failure**. **Striations** are **not observed** for **all metals** that experience fatigue.

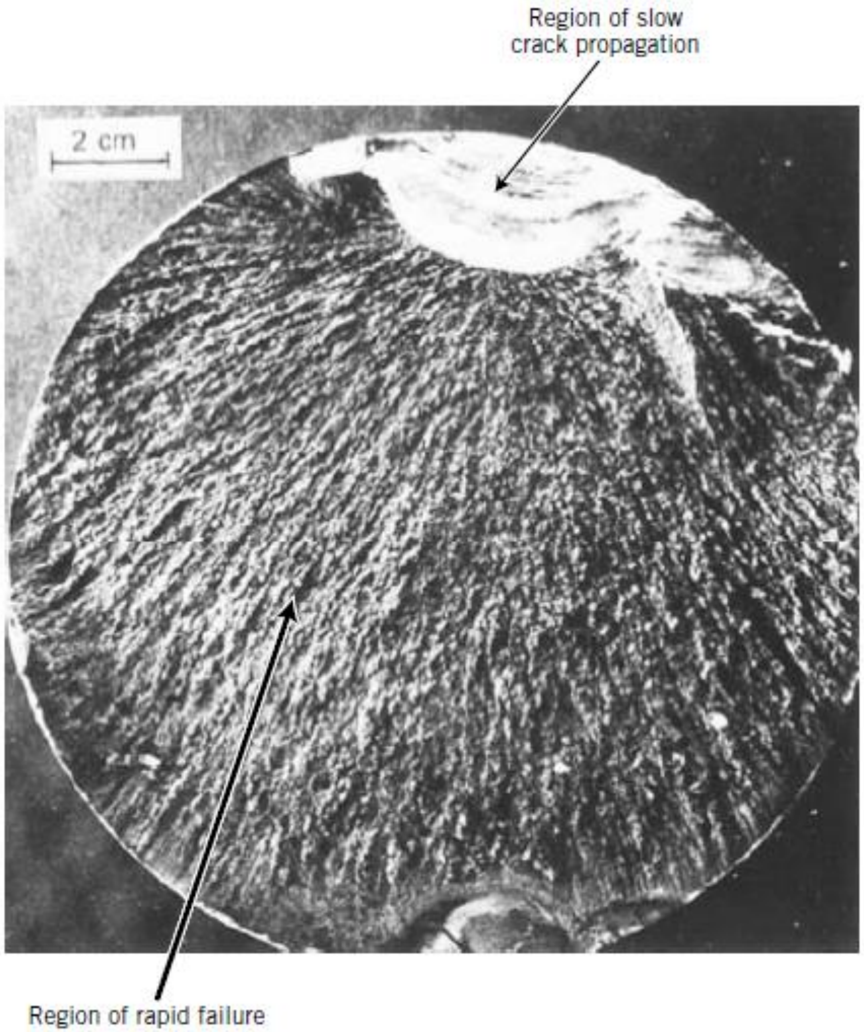
- Furthermore, the likelihood of the appearance of striations may **depend on stress state**. **Striation detectability decreases** with the passage of **time** because of the formation of **surface corrosion** products **and/or oxide films**.

- Also, during stress cycling, **striations** may be **destroyed** by **abrasive action** as **crack** mating surfaces rub against one another.

6.9. Crack Initiation and Propagation

- One final comment regarding fatigue failure surfaces: **Beachmarks and striations do not appear on the region over which the rapid failure occurs.**

- Rather, the **rapid failure** may be either **ductile** or **brittle**; evidence of **plastic deformation** will be present for **ductile failure** and absent for brittle failure. This region of failure may be noted in the figure.



Fatigue failure surface. A crack formed at the top edge. The smooth region also near the top corresponds to the area over which the crack propagated slowly. Rapid failure occurred over the area having a dull and fibrous texture (the largest area). Approximately 0.5X.

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6.10. Factors That Affect Fatigue Life

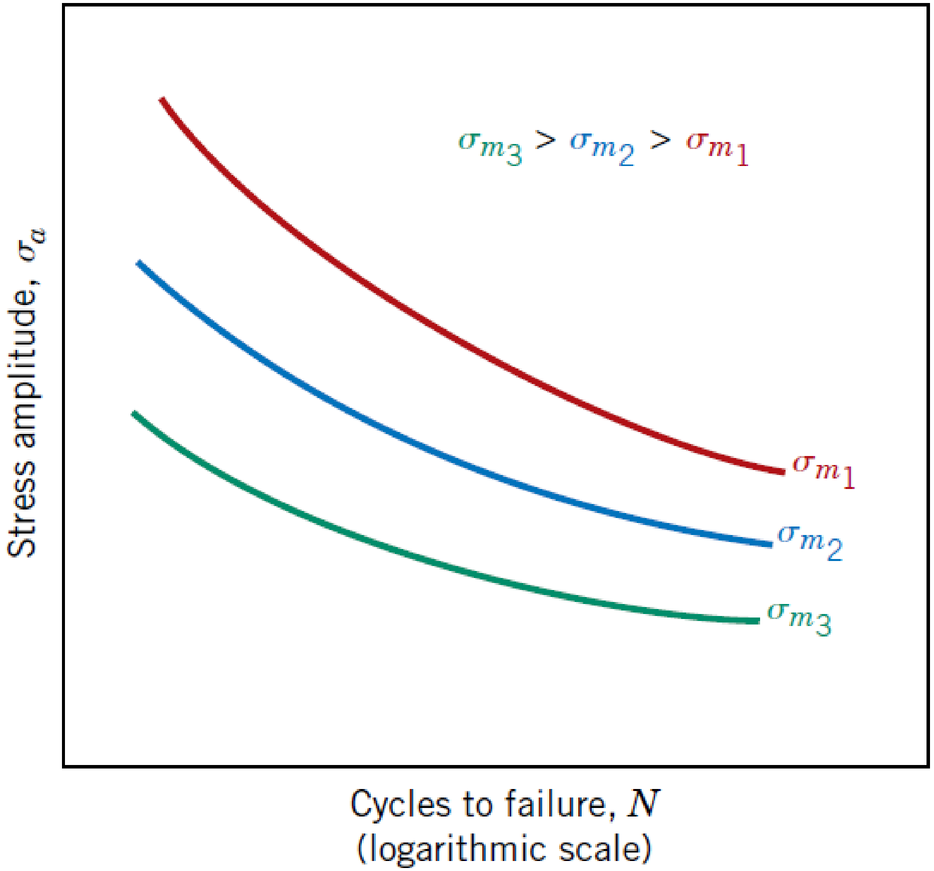
- As mentioned previously, the **fatigue** behavior of engineering materials is **highly sensitive** to a number of **variables**, including **mean stress level**, **geometric design**, **surface effects**, and **metallurgical** variables, as well as the **environment**.

- This section is devoted to a **discussion** of **these factors** and to **measures** that may be taken to improve the fatigue **resistance** of structural components.

6.10. Factors That Affect Fatigue Life

Mean Stress

- The **dependence** of **fatigue life** on **stress amplitude** is represented on the ***S–N*** plot.
- Such data are taken for a **constant mean stress σ_m**, often for the reversed cycle situation (**$\sigma_m = 0$**).
- Mean stress, however, also affects fatigue life; this influence may be represented by a series of ***S–N*** curves, each measured at a different **σ_m**, as depicted schematically in the Figure.
- As may be noted, **increasing** the **mean stress level** leads to a **decrease** in **fatigue life**.



Demonstration of the influence of mean stress σ_m on S–N fatigue behavior.

6.10. Factors That Affect Fatigue Life

Surface Effects

- For **many common** loading **situations**, the **maximum stress** within a component or structure occurs at its **surface**.
- Consequently, **most cracks** leading to **fatigue failure** originate at **surface** positions, specifically at stress amplification sites.
- Therefore, it has been observed that **fatigue life** is especially **sensitive** to the **condition** and **configuration** of the component **surface**.
- Numerous **factors influence** fatigue **resistance**, the proper **management** of which will lead to an **improvement** in **fatigue life**.
- These include **design** criteria as well as various **surface treatments**.

6.10. Factors That Affect Fatigue Life

Surface Effects: Design Factors

- The **design** of a component can have a significant **influence** on its **fatigue characteristics**.

- **Any notch** or **geometrical discontinuity** can act as a **stress raiser** and fatigue crack initiation site; these design features include **grooves**, **holes**, **keyways**, **threads**, and so on.

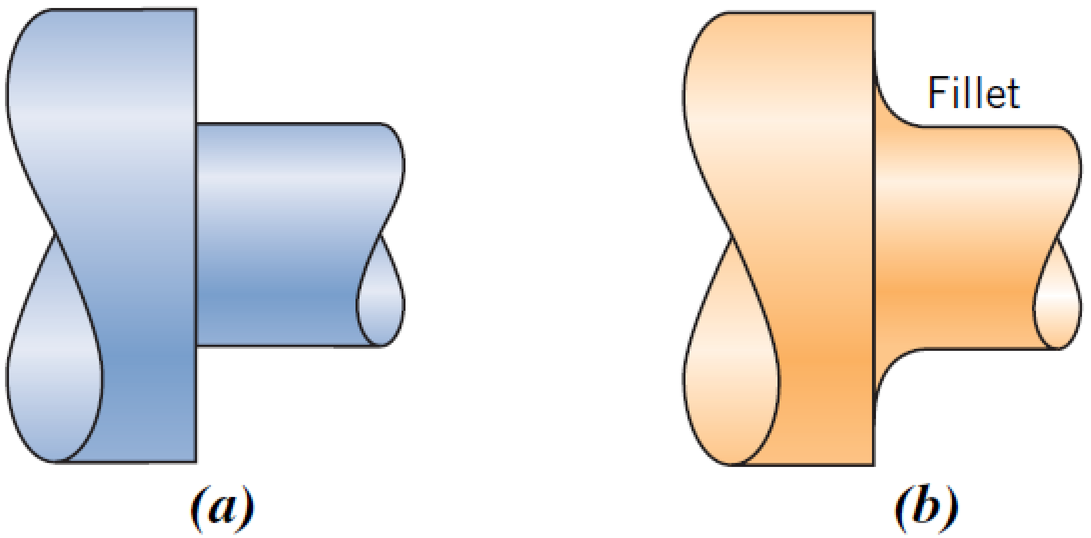
- The **sharper** the **discontinuity** (i.e., the smaller the radius of curvature), the more **severe** the **stress concentration**.

- The **probability** of **fatigue failure** may be **reduced** by **avoiding** (when possible) these **structural irregularities** or by making design modifications by which sudden contour changes leading to sharp corners are eliminated.

6.10. Factors That Affect Fatigue Life

Surface Effects: Design Factors

- **For example**, calling for **rounded fillets** with **large radii** of **curvature** at the point where there is a change in diameter for a rotating shaft (Figure).



Demonstration of how design can reduce stress amplification. (a) Poor design: sharp corner. (b) Good design: fatigue lifetime is improved by incorporating a rounded fillet into a rotating shaft at the point where there is a change in diameter.

6.10. Factors That Affect Fatigue Life

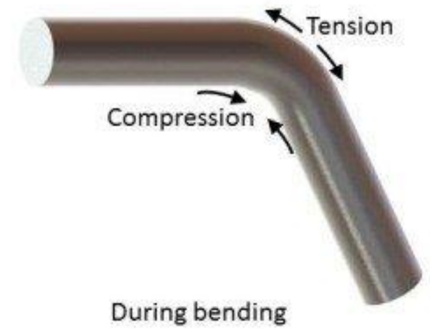
Surface Effects: Surface Treatments

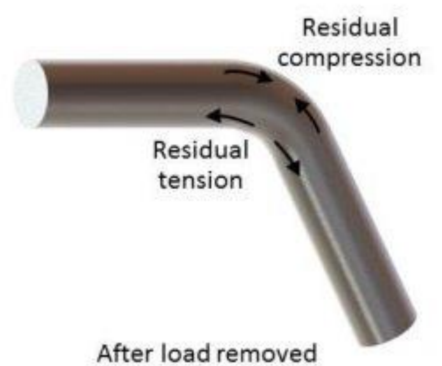
- **During machining** operations, **small scratches** and **grooves** are invariably introduced into the workpiece surface by **cutting-tool** action. These surface markings can limit the fatigue life.

- It has been observed that **improving** the **surface finish** by **polishing** enhances fatigue life **significantly**.

- **One** of the **most effective methods** of increasing fatigue performance is by **imposing residual compressive stresses** within a thin outer surface layer. Thus, a surface **tensile stress** of **external** origin is **partially nullified** and **reduced** in **magnitude** by the residual compressive stress. The net effect is that the likelihood of **crack formation** and therefore of **fatigue failure** is **reduced**.

- **Residual compressive stresses** are commonly introduced into **ductile metals mechanically** by localized plastic deformation within the outer surface region.

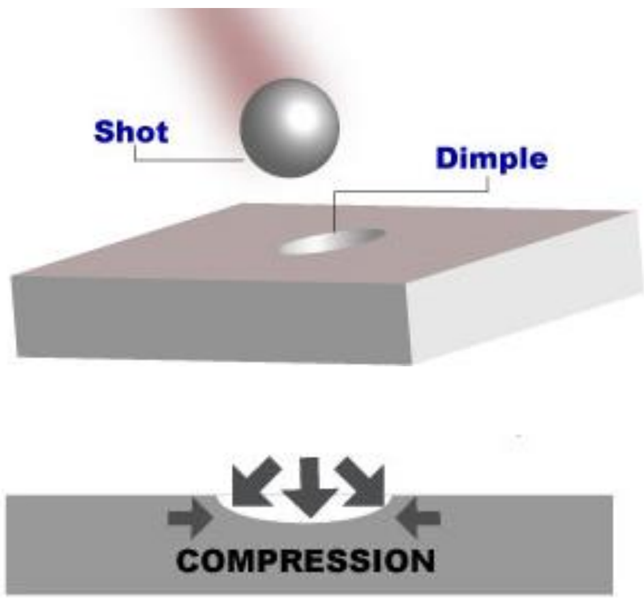


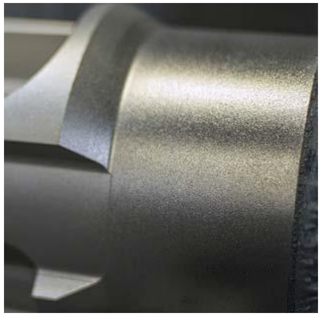


6.10. Factors That Affect Fatigue Life

Surface Effects: Surface Treatments

- **Commercially**, this is often accomplished by a process termed **shot peening.**
- **Small**, **hard particles** (**shot**) having diameters within the range of **0.1 to 1 mm** are projected at **high velocities** onto the surface to be treated.
- The resulting deformation induces **compressive stresses** to a **depth** of between **one-quarter and one-half of the shot diameter**.

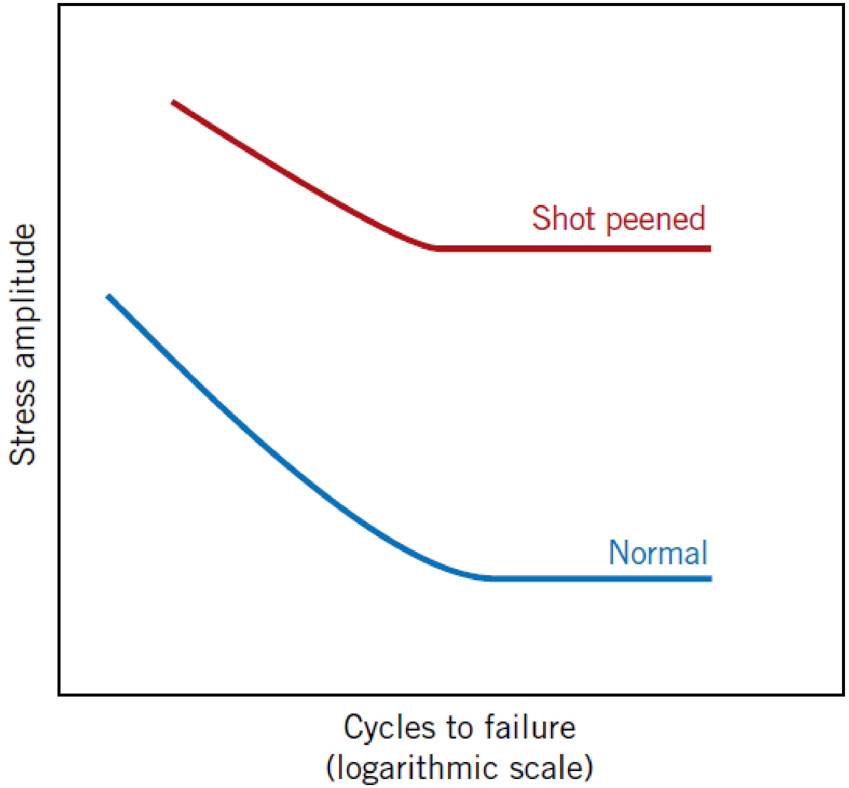




6.10. Factors That Affect Fatigue Life

Surface Effects: Surface Treatments

- The influence of shot peening on the fatigue behavior of steel is demonstrated schematically in the figure.

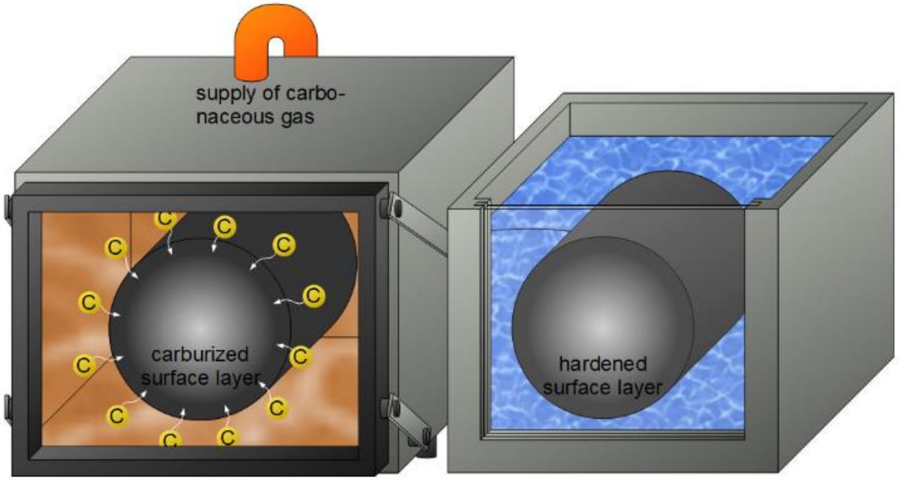


Schematic S–N fatigue curves for normal and shot-peened steel.

6.10. Factors That Affect Fatigue Life

Surface Effects: Surface Treatments

- **Case hardening** is a **technique** by which both **surface hardness** and **fatigue life** are **enhanced** for **steel alloys**.
- This is accomplished by a **carburizing** or **nitriding** process by which a component is exposed to a **carbonaceous** or **nitrogenous atmosphere** at **elevated temperature**.
- A **carbon-** or **nitrogen-rich** outer **surface layer** (or **case**) is introduced by **atomic diffusion** from the **gaseous phase**.
- The case is normally on the order of **1 mm deep** and is **harder** than the inner core of material.



6.10. Factors That Affect Fatigue Life

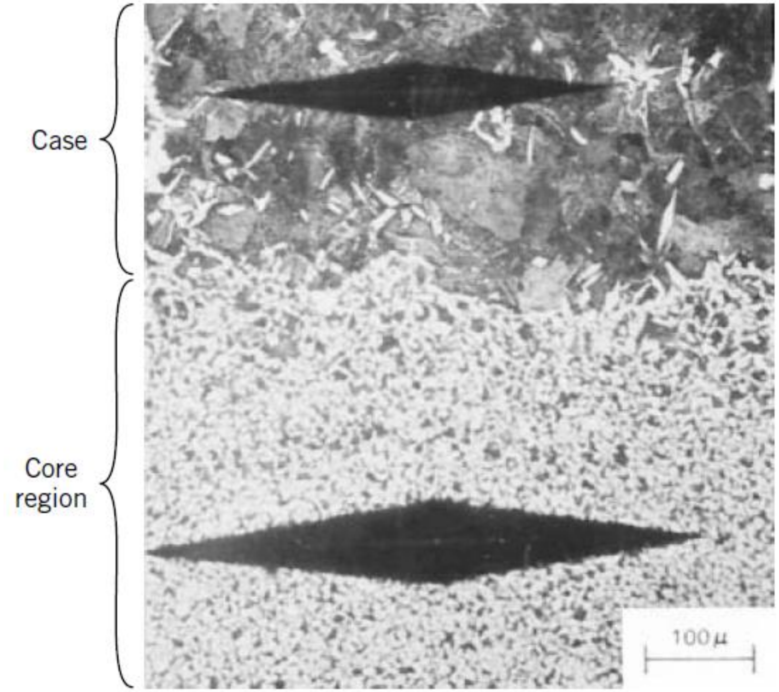
Surface Effects: Surface Treatments

- The improvement of fatigue properties results from **increased hardness** within the **case**, as well as the desired residual compressive stresses the formation of which attends the carburizing or nitriding process.

- The **increase** in **case hardness** is demonstrated in the photomicrograph in the figure.

- The **dark** and **elongated diamond** shapes are **Knoop microhardness indentations**.

- The **upper indentation**, lying within the carburized layer, is **smaller** than the core **indentation**.



Photomicrograph showing both core (bottom) and carburized outer case (top) regions of a case-hardened steel. The case is harder, as attested by the smaller microhardness indentation. 100x.

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6.11. Environmental Effects

- Environmental factors may also affect the fatigue behavior of materials.

- A few brief comments will be given relative to two types of **<u>environment-assisted fatigue failure</u>**: **Thermal fatigue** and **Corrosion fatigue**.

Deformation of railway due to thermal expansion

Expansion gap (railway joint)

6.11. Environmental Effects

Thermal Fatigue

- Thermal fatigue is normally induced at **elevated temperatures** by **fluctuating thermal stresses**; mechanical stresses from an external source need not be present.

- The origin of these thermal stresses is the restraint to the **dimensional expansion and/or contraction** that would normally occur in a structural member with variations in temperature.

- The **magnitude of a thermal stress** developed by a temperature change **T** depends on the **coefficient** of **thermal expansion α_l** and the modulus of elasticity **E** according to

$$\boxed{\sigma = \alpha_l E \Delta T}$$

- Thermal stresses **do not arise** if this **mechanical restraint** is **absent**.

- Therefore, one **obvious way** to **prevent** this type of fatigue is to **eliminate**, **or** at least **reduce**, the **restraint source**, thus allowing unhindered dimensional changes with temperature variations, or to choose materials with appropriate **physical properties**.

6.11. Environmental Effects

Corrosion Fatigue

- **Failure** that occurs by the simultaneous action of a **cyclic stress** and **chemical attack** is termed **corrosion** fatigue.

- Corrosive environments have a **deleterious influence** and produce **shorter fatigue lives**. **Even normal ambient atmosphere** affects the fatigue behavior of some materials.

- **Small pits** may form as a result of **chemical reactions** between the **environment** and the **material**, which may serve as **points of stress concentration** and therefore as **crack nucleation sites**.

- In addition, the **crack propagation rate** is **enhanced** as a result of the **corrosive** environment.

- The nature of the stress cycles influences the fatigue behavior; **for example**, **lowering** the load application **frequency** leads to **longer periods** during which the **opened crack** is in **contact with the environment** and to a **reduction** in the fatigue **life**.

6.11. Environmental Effects

Corrosion Fatigue

- Several approaches to **corrosion fatigue prevention** exist.

- On one hand, we can take measures to **reduce** the **rate of corrosion** by some **chemical techniques**, **for example**, apply **protective** surface **coatings**, select a more **corrosion-resistant** material, and **reduce the corrosiveness** of the **environment**.

- On the other hand, it might be advisable to take actions to **minimize** the **probability** of **normal fatigue failure**, as outlined previously—**for example**, **reduce** the applied **tensile stress** level and **impose residual compressive stresses** on the surface of the member.

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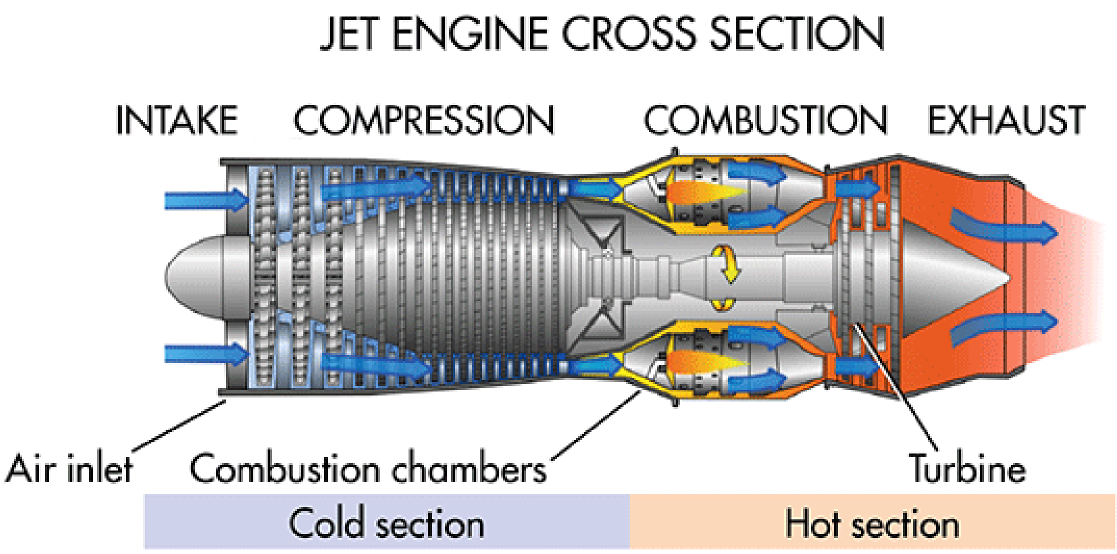
Introduction

- Materials are often placed in **service at elevated temperatures** and exposed to **static mechanical stresses** (e.g., **turbine rotors in jet engines** and **steam generators** that experience centrifugal stresses; high-pressure **steam lines**).

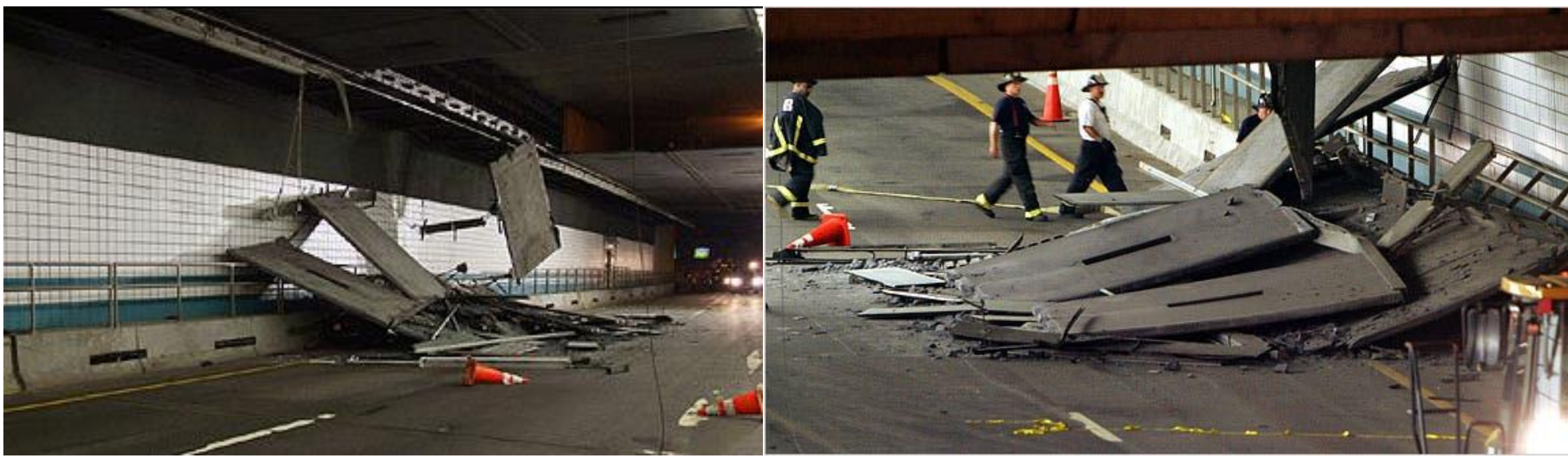
- Deformation under such circumstances is termed **creep**.

- Defined as the **time-dependent and permanent deformation of materials** when subjected to a **constant load or stress**, creep is normally an **undesirable phenomenon** and is often the **limiting** factor in the **lifetime** of a part.



Introduction

- It is observed in **all materials types**; for **metals**, it becomes important only for temperatures **greater than about $0.4T_m$**, where T_m is the **absolute melting temperature.**
- **Amorphous polymers**, which include **plastics** and **rubbers**, are especially **sensitive** to **creep deformation**.



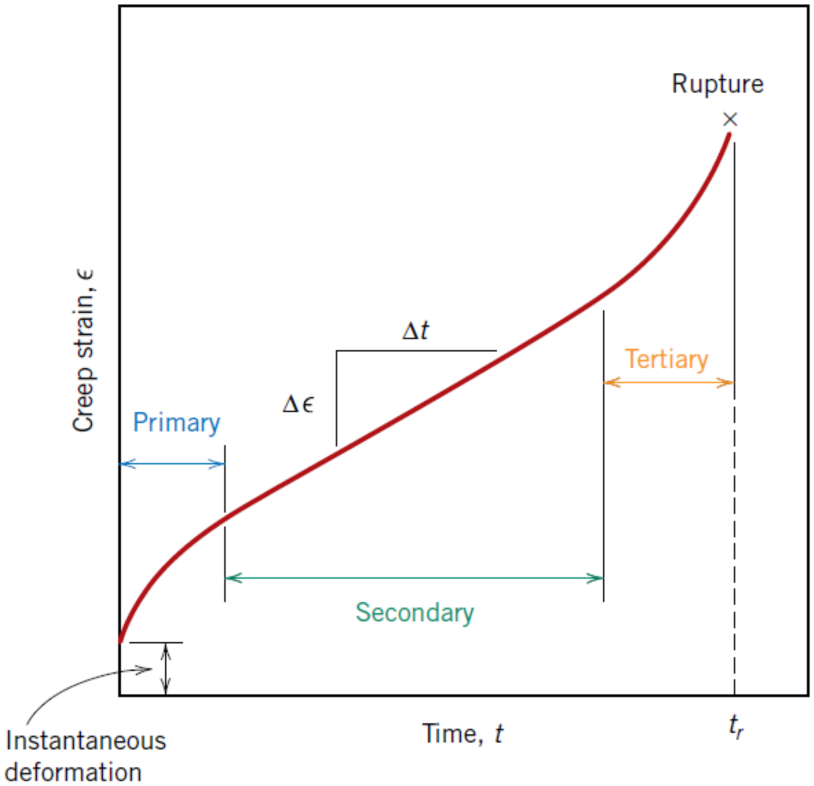
A woman died in the collapse of the ceiling of a "Big Dig" tunnel in Boston (2006). Creep of polymer (epoxy glue).

6.12. Generalized Creep Behavior

- A **typical creep test** consists of subjecting a specimen to a **constant load or stress** while maintaining the **temperature constant**; deformation or strain is measured and plotted as a function of elapsed time.

- **Most tests** are the **constant-load** type, which yield information of an engineering nature; constant-stress tests are employed to provide a **better understanding** of the **mechanisms** of **creep**.

- The following **figure** is a schematic representation of the typical **constant-load creep behavior** of metals.



Typical creep curve of strain versus time at constant load and constant elevated temperature.
The minimum creep rate Δε/Δt is the slope of the linear segment in the secondary region.
Rupture lifetime t_r is the total time to rupture.

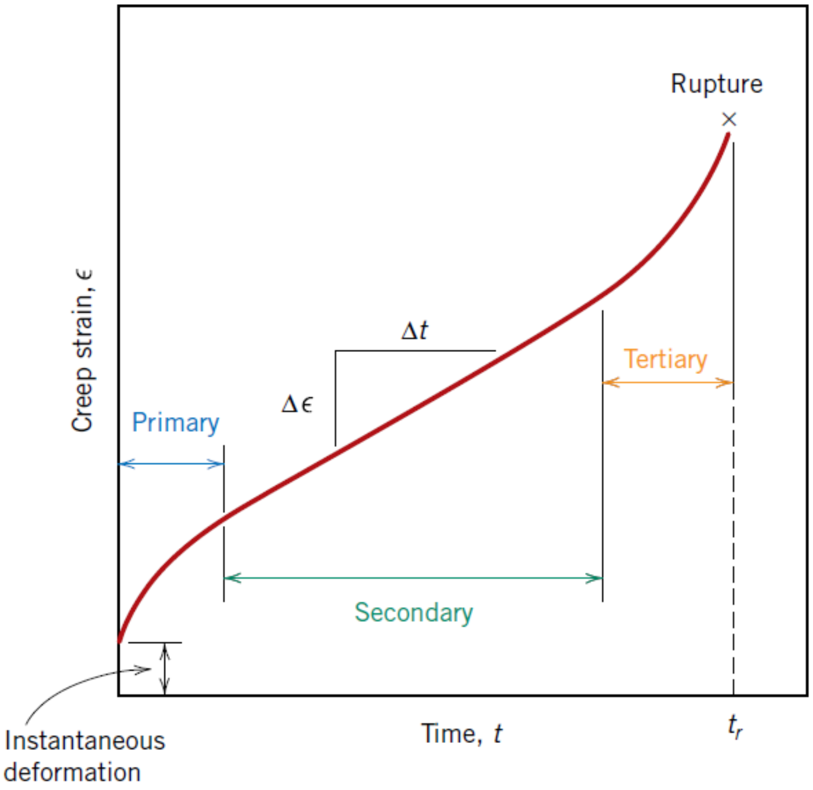
6.12. Generalized Creep Behavior

- Upon application of the load, there is an **instantaneous deformation**, as indicated in the figure, that is **totally elastic**.

- The resulting creep curve consists of **three regions**, each of which has its own **distinctive strain–time feature**.

- **Primary** or **transient creep** occurs first, typified by a **continuously decreasing creep rate**—that is, the slope of the curve decreases with time.

- This suggests that the **material** is **experiencing** an **increase** in **creep resistance** or **strain hardening** — **deformation becomes more difficult as the material is strained**.

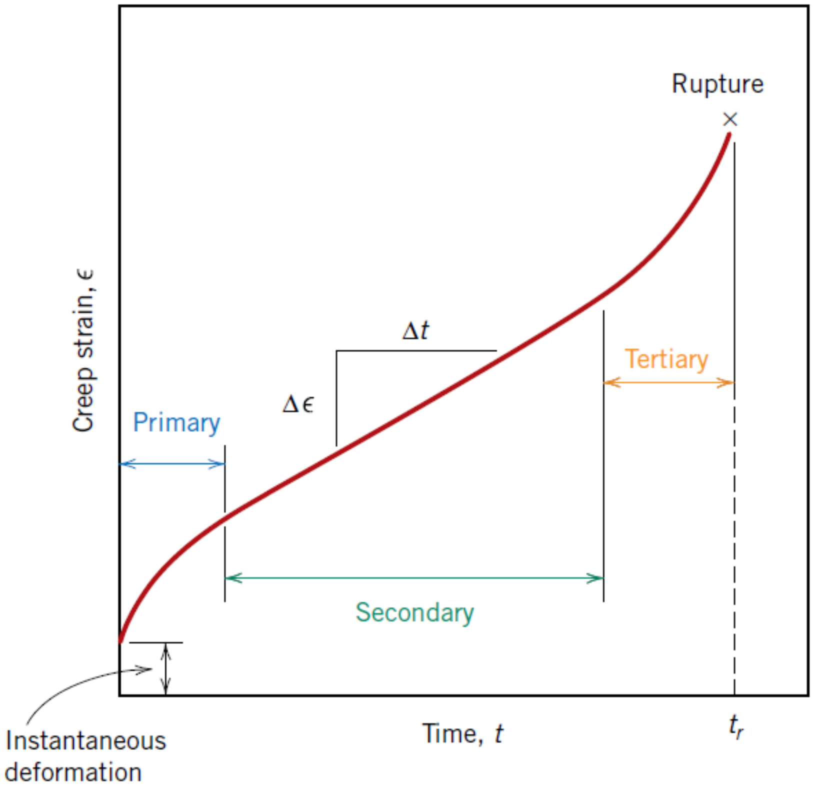


Typical creep curve of strain versus time at constant load and constant elevated temperature.
The minimum creep rate $\Delta\varepsilon/\Delta t$ is the slope of the linear segment in the secondary region.
Rupture lifetime t_r is the total time to rupture.

6.12. Generalized Creep Behavior

- For **secondary** creep, sometimes termed **steady-state creep**, the **rate** is **constant**—that is, the plot becomes **linear**. This is often the stage of creep that is of the **longest duration**.

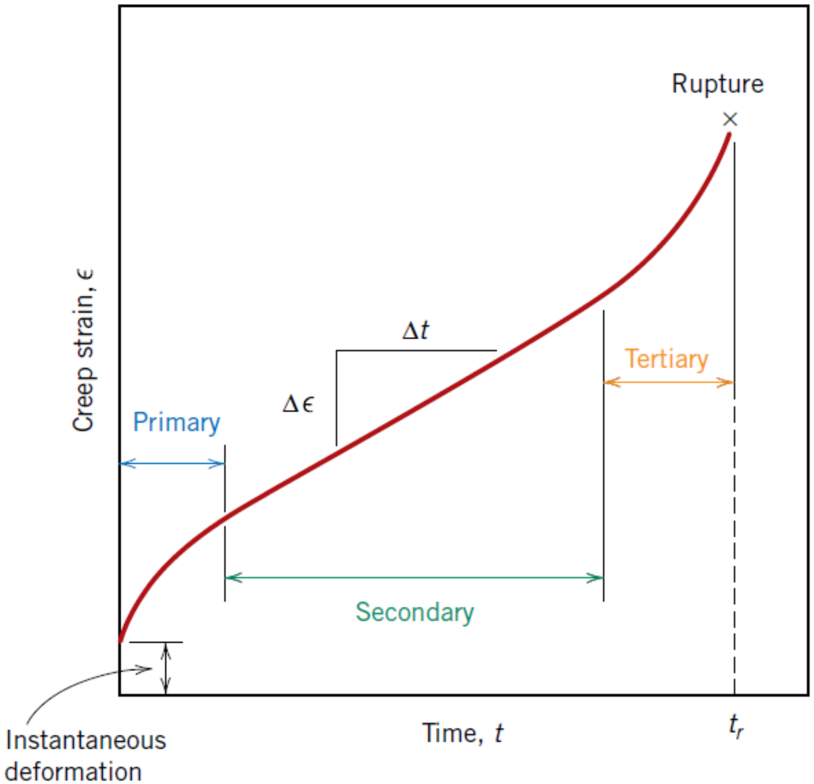
- The constancy of creep rate is explained on the basis of a **balance** between the competing processes of **strain hardening** and **recovery**, recovery being the process by which a material becomes softer and retains its ability to experience deformation.



Typical creep curve of strain versus time at constant load and constant elevated temperature.
The minimum creep rate $\Delta\varepsilon/\Delta t$ is the slope of the linear segment in the secondary region.
Rupture lifetime t_r is the total time to rupture.

6.12. Generalized Creep Behavior

- Finally, for **tertiary creep**, there is an **acceleration** of the **rate** and **ultimate failure**.
- This failure is frequently termed **rupture** and results from **microstructural and/or metallurgical changes**—for example, **grain boundary separation**, and the formation of **internal cracks**, cavities, and **voids**.
- Also, for **tensile loads**, a **neck** may form at **some point** within the deformation region.
- These all lead to a **decrease** in the **effective cross-sectional** area and an **increase** in **strain rate**.



Typical creep curve of strain versus time at constant load and constant elevated temperature.
The minimum creep rate $\Delta\varepsilon/\Delta t$ is the slope of the linear segment in the secondary region.
Rupture lifetime t_r is the total time to rupture.

6.12. Generalized Creep Behavior

- For **metallic materials**, most **creep tests** are conducted in **uniaxial tension** using a specimen having the **same geometry** as for **tensile tests**.

- However, **uniaxial compression** tests are **more appropriate** for **brittle materials**; these provide a better measure of the intrinsic creep properties **because** there is **no stress amplification** and **crack propagation**, as with tensile loads.

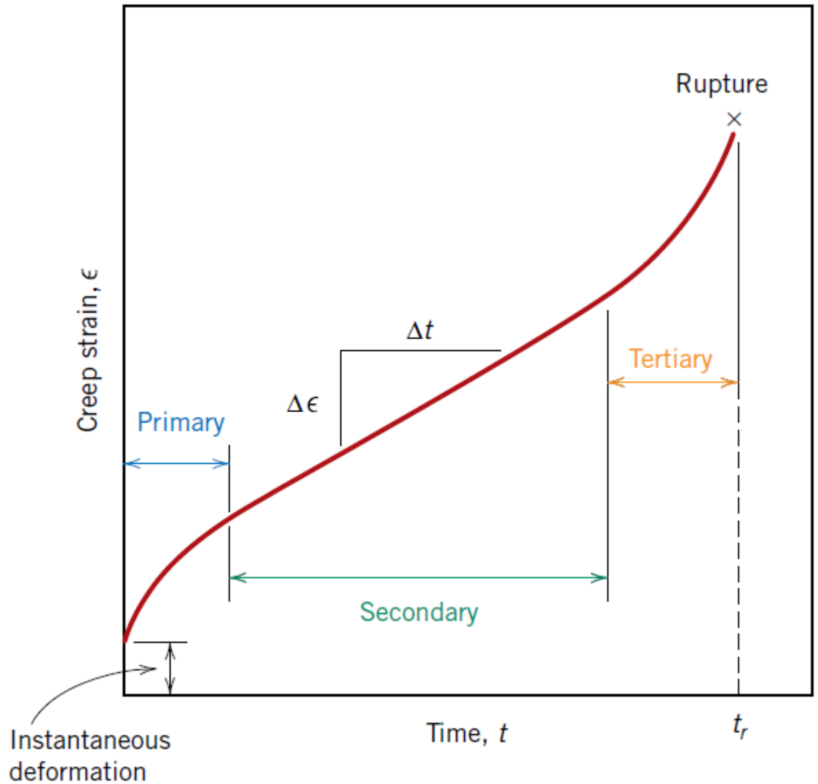
- **Compressive test specimens** are usually **right cylinders** or **parallelepipeds** having l**ength-to-diameter ratios** ranging from about **2 to 4**.

- **For most materials**, creep properties are virtually **independent** of **loading direction**.

6.12. Generalized Creep Behavior

- Possibly the **most important** parameter from a creep test is the **slope** of the **secondary** portion of the creep curve ($\Delta\epsilon/\Delta t$); this is often called the **minimum or steady-state creep rate** $\dot{\epsilon}_s$.

- It is the **engineering design parameter** that is **considered** for **long-life applications**, such as a **nuclear power plant component** that is scheduled to operate for several decades, and when failure or too much strain is not an option.



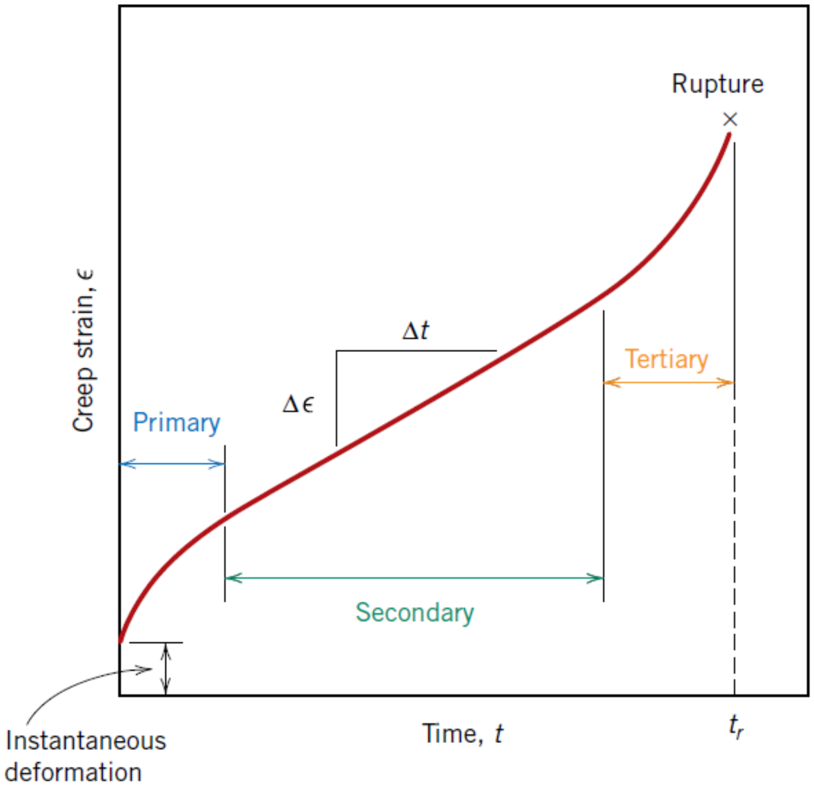
Typical creep curve of strain versus time at constant load and constant elevated temperature.
The minimum creep rate $\Delta\varepsilon/\Delta t$ is the slope of the linear segment in the secondary region.
Rupture lifetime t_r is the total time to rupture.

6.12. Generalized Creep Behavior

- **However**, for many **relatively short-life creep situations** (e.g., **turbine** blades in **military aircraft** and **rocket** motor **nozzles),** **time to rupture**, or the **rupture lifetime t_r**, is the **dominant design consideration**; it is also indicated in the figure.

- Of course, **for its determination**, creep tests must be conducted to the point of failure; these are termed **creep rupture tests.**

- Thus, knowledge of these creep characteristics of a material allows the design engineer to ascertain its suitability for a specific application.



Typical creep curve of strain versus time at constant load and constant elevated temperature.
The minimum creep rate $\Delta\varepsilon/\Delta t$ is the slope of the linear segment in the secondary region.
Rupture lifetime t_r is the total time to rupture.

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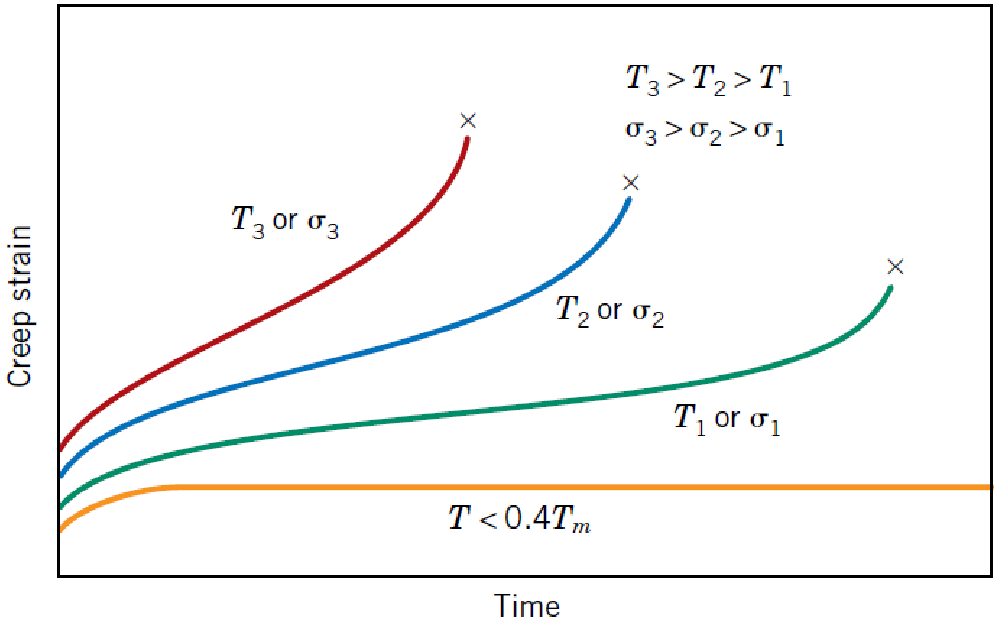
6.13. Stress and Temperature Effects

- **Both temperature** and the **level** of the **applied stress** influence the **creep characteristics**.

- At a **temperature** substantially **below 0.4T_m**, and **after** the **initial deformation**, the **strain is virtually independent of time**.

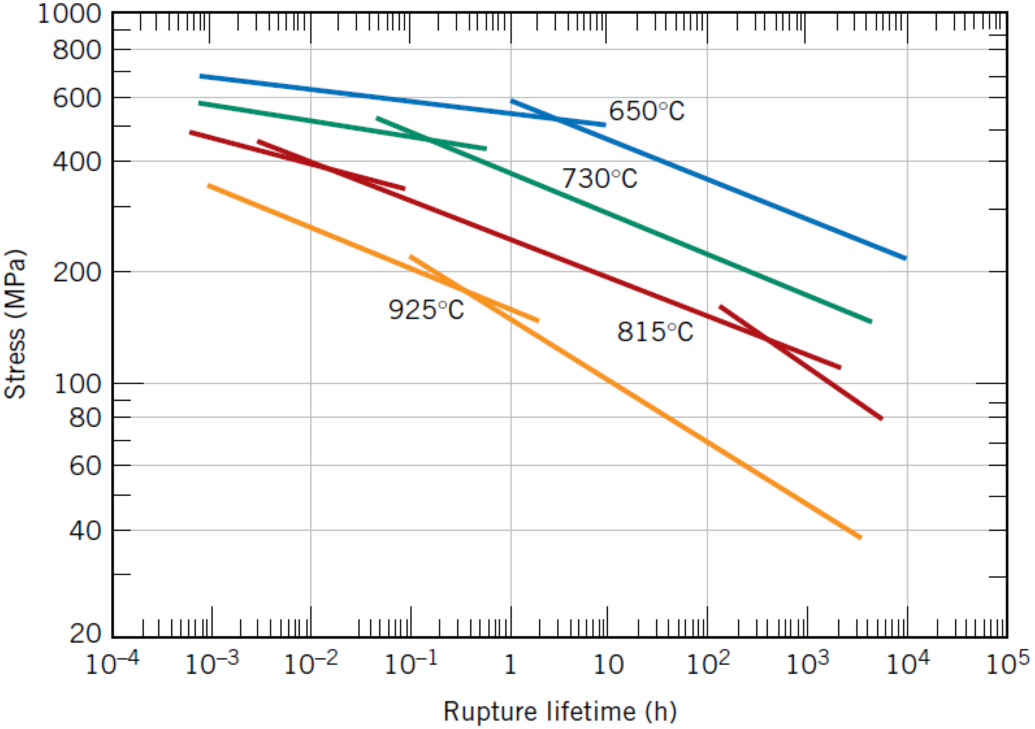
- With **either increasing** stress or temperature, the following will be noted: **(1)** the **instantaneous strain** at the time of stress application **increases**, **(2) the steady-state creep rate increases**, and **(3) the rupture lifetime decreases.**



Influence of stress s and temperature T on creep behavior.

6.13. Stress and Temperature Effects

- The **results** of creep rupture tests are most commonly presented as the **logarithm** of **stress** versus the **logarithm** of **rupture lifetime**.
- This **figure** is one such plot for an S-590 alloy in which a set of linear relationships can be seen to exist at each temperature.
- **For some alloys** and **over** relatively **large stress ranges**, **nonlinearity** in these curves is observed.



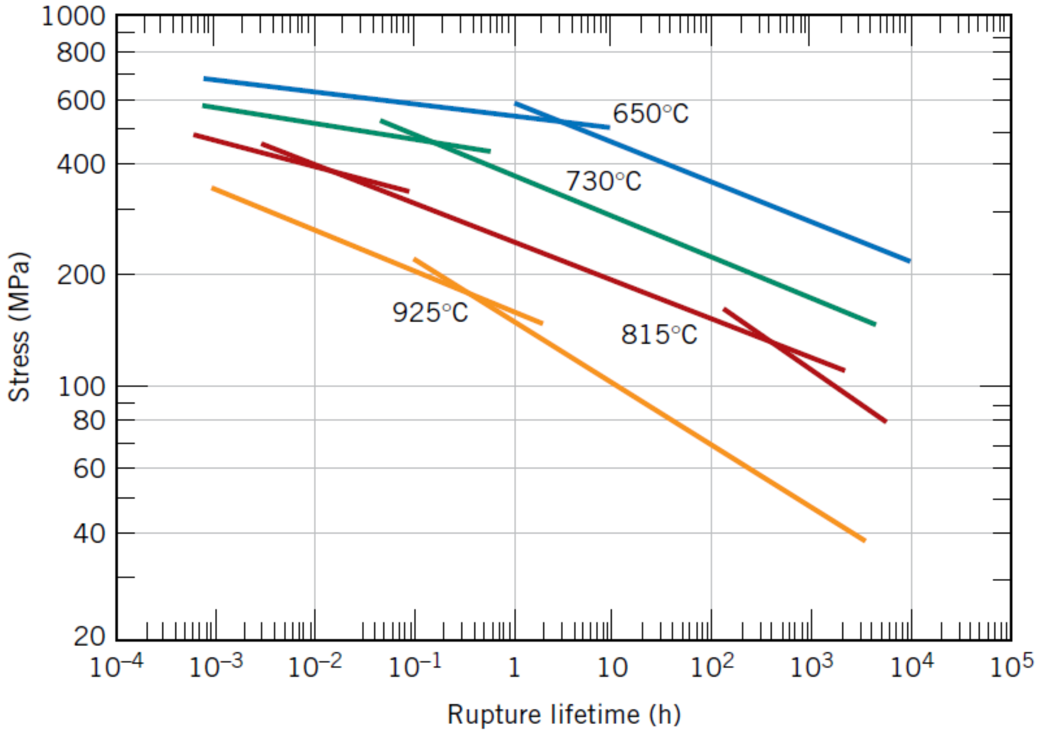
Stress (logarithmic scale) versus rupture lifetime (logarithmic scale) for an S-590 alloy at four temperatures.

6.13. Stress and Temperature Effects

- Empirical relationships have been developed in which the **steady-state creep rate** as a **function** of **stress** and **temperature** is expressed. Its dependence on **stress** can be written:

$$\boxed{\dot{\epsilon}_s = K_1 \sigma^n}$$

where K_1 and n are material constants.



Stress (logarithmic scale) versus rupture lifetime (logarithmic scale) for an S-590 alloy at four temperatures.

6.13. Stress and Temperature Effects

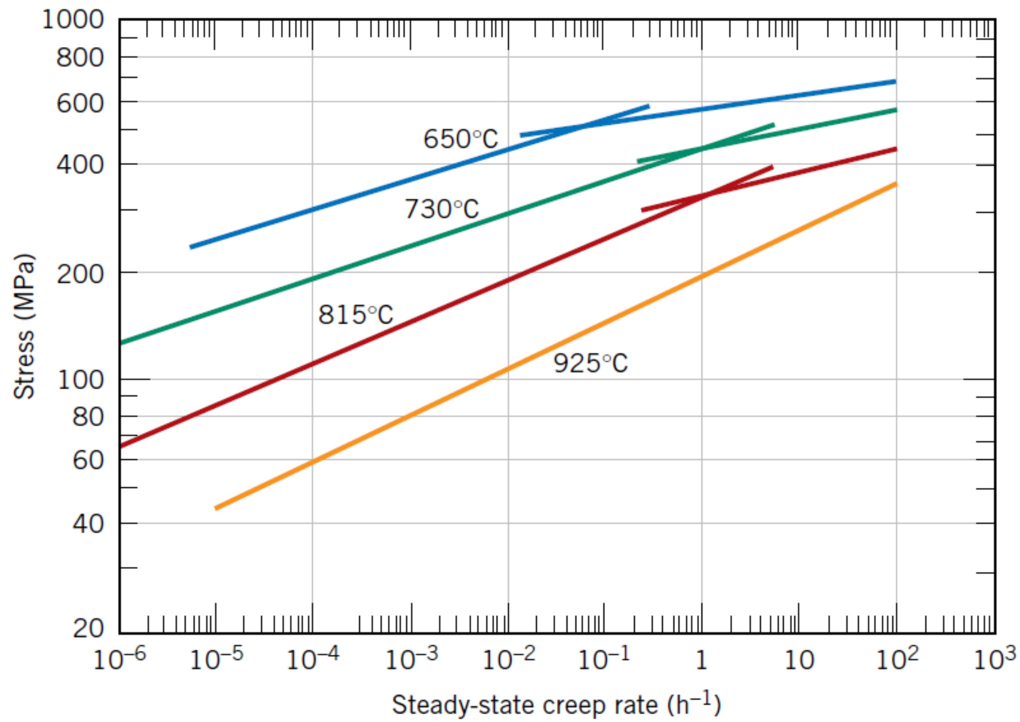
- A plot of the logarithm of $\dot{\epsilon}$ versus the logarithm of σ yields a **straight line with slope** of n; this is shown in the figure for an S-590 alloy at four temperatures.

- Clearly, one or two straight-line segments are drawn at each temperature.

- Now, when the **temperature** is **included**, **creep strain rate** will be written:

$$\boxed{\dot{\epsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)}$$

where K_2 and Q_c are constants; Q_c is termed the activation energy for creep.



Stress (logarithmic scale) versus steady-state creep rate (logarithmic scale) for an S-590 alloy at four temperatures.

6.13. Stress and Temperature Effects

- Several **theoretical mechanisms** have been proposed to **explain** the **creep** behavior for **various materials**; these mechanisms involve **stress-induced vacancy diffusion**, **grain boundary diffusion**, **dislocation** motion, and **grain boundary sliding**.

- **Each** leads to a **different value** of the stress **exponent** ***n*** in the previous equations.

- It has been **possible** to **elucidate the creep mechanism** for a particular material by **comparing** its **experimental** ***n*** value with values **predicted** for the **various mechanisms**.

- **Creep data** of this nature are represented pictorially for some well-studied systems in the form of **stress–temperature diagrams**, which are termed **deformation mechanism maps**.

- These **maps indicate** stress–temperature **regimes** (or **areas**) over which **various mechanisms operate**. Constant-strain-rate contours are often also included.

- Thus, for some creep situation, given the appropriate deformation **mechanism map and any two** of the three **parameters**—**temperature, stress level, and creep strain rate**—the **third** parameter may be **determined**.

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6.14. Data Extrapolation Methods

- The need often arises for **engineering creep data** that are **impractical** to **collect** from **normal laboratory tests**.

- This is especially true for prolonged exposures (on the **order of years**). One solution to this problem involves performing creep and/or creep rupture **tests at temperatures** in **excess** of those **required**, for **shorter time** periods, and at a **comparable stress level**, and then making a suitable **extrapolation** to the **in-service condition**.

- A commonly used **extrapolation** procedure employs the **Larson–Miller parameter**, ***m***, defined as:

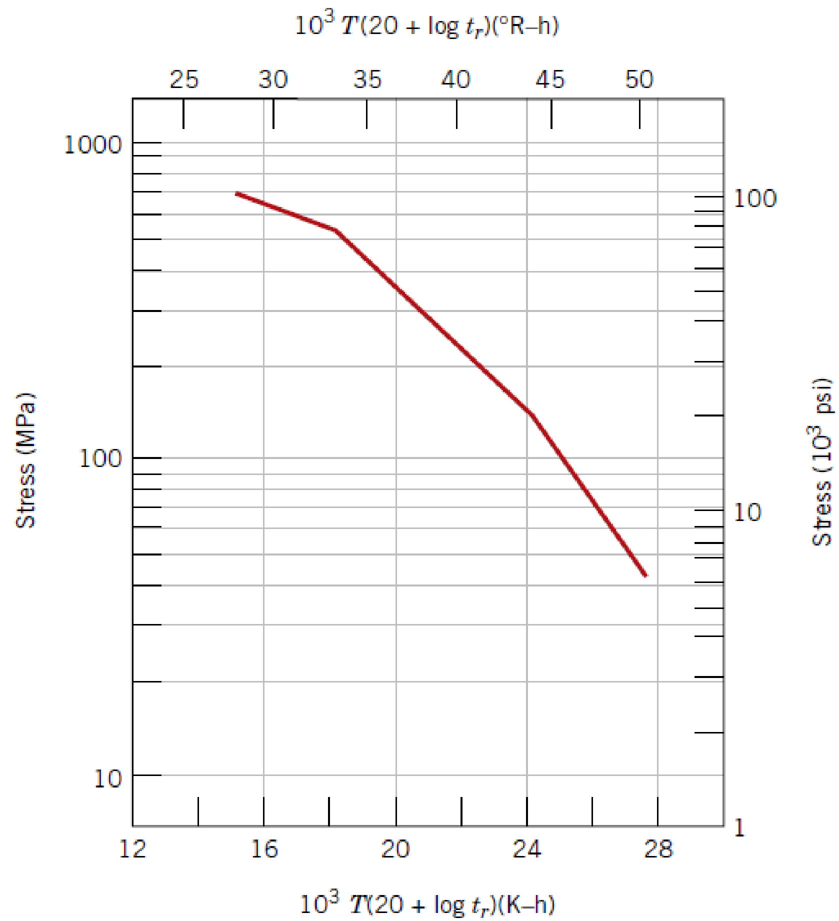
$$\boxed{m = T(C + \log t_r)}$$

where C is a **constant** (usually on the order of **20**), for T in **Kelvin** and the rupture lifetime t_r in hours.

6.14. Data Extrapolation Methods

- The **rupture lifetime** of a given material measured at some specific **stress level** varies with **temperature** such that this parameter ***m*** **remains constant (for the same stress)**.

- Alternatively, the data may be **plotted** as the logarithm of **stress** versus the **Larson–Miller parameter**, as shown.



Logarithm of stress versus the Larson–Miller parameter for an S-590 alloy.

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6.15. Alloys For High-temperature Use

- **Several factors** affect the **creep characteristics** of metals. These include **melting temperature**, **elastic modulus**, and **grain size**.

- In general, the **higher** the **melting temperature**, the **greater** the **elastic modulus**; the **larger** the **grain size**, the **better** a material's **resistance to creep**.

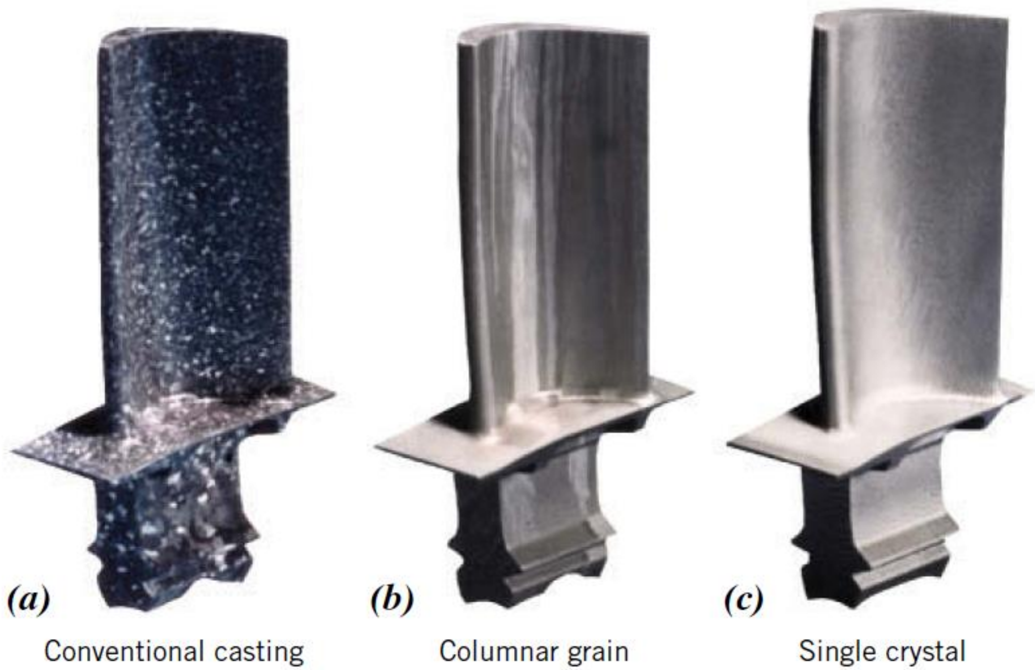
- Relative to grain size, **smaller grains** permit **more grain boundary sliding**, which results in **higher creep rates**. This effect may be **contrasted to the influence of grain size on the mechanical behavior at low temperatures** [i.e., increase in both strength and toughness].

- **Stainless steels** and the **superalloys** are especially **resilient** to creep and are commonly **employed** in **high-temperature** service **applications**.

- The creep resistance of the **superalloys** is **enhanced by solid-solution alloying** and also by the **formation** of **precipitate phases**.

6.15. Alloys For High-temperature Use

- In addition, **advanced processing techniques** have been utilized; one such technique is **directional solidification**, which produces either **highly elongated grains** or **single-crystal components**.



(a) Polycrystalline turbine blade that was produced by a conventional casting technique. High-temperature creep resistance is improved as a result of an oriented columnar grain structure (b) produced by a sophisticated directional solidification technique. Creep resistance is further enhanced when single-crystal blades (c) are used.