Fatigue life prediction of critical metallic components based on strain energy density

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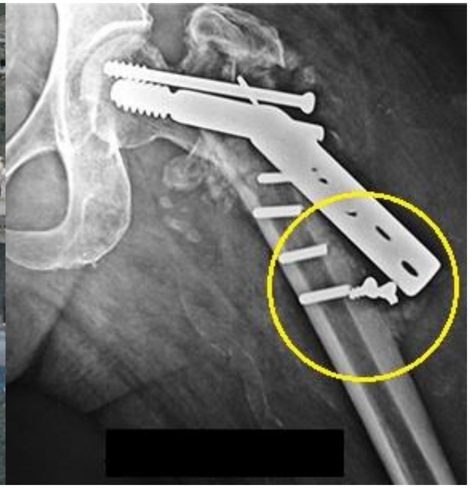
Outline

- Introduction
- Material and method
- Total fatigue toughness
- Results
- Conclusions

Definition of fatigue

- Fatigue is the reduced material resistance under fluctuating stresses or reversals, which may culminate in cracks or failure after a number of cycles.
- Fatigue failure generally occurs at stress levels below yield stress when subjected to cyclic loading.
- At least half of all mechanical failures are due to fatigue which most of them are unexpected failures.



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Fatigue in different fields

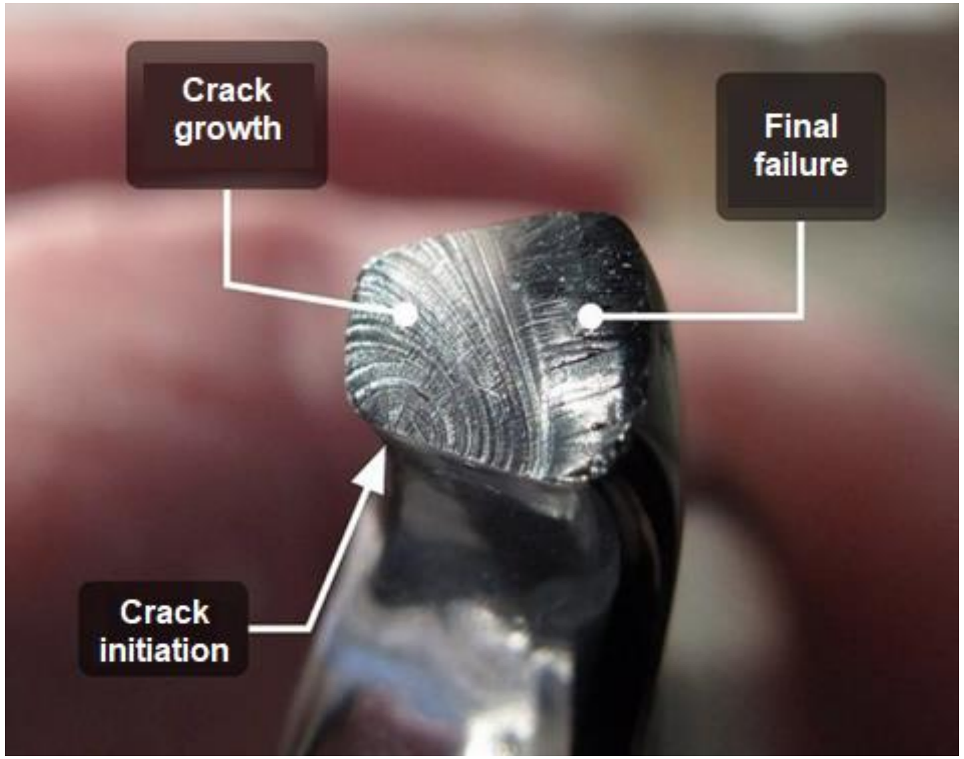
❑ Fatigue failures occur in every field of engineering:

- Bridges involving civil engineers
- Automobiles involving mechanical engineers
- Aircraft involving aeronautical engineers
- Heart valve implants involving biomedical engineers
- Pressure vessels involving chemical engineers

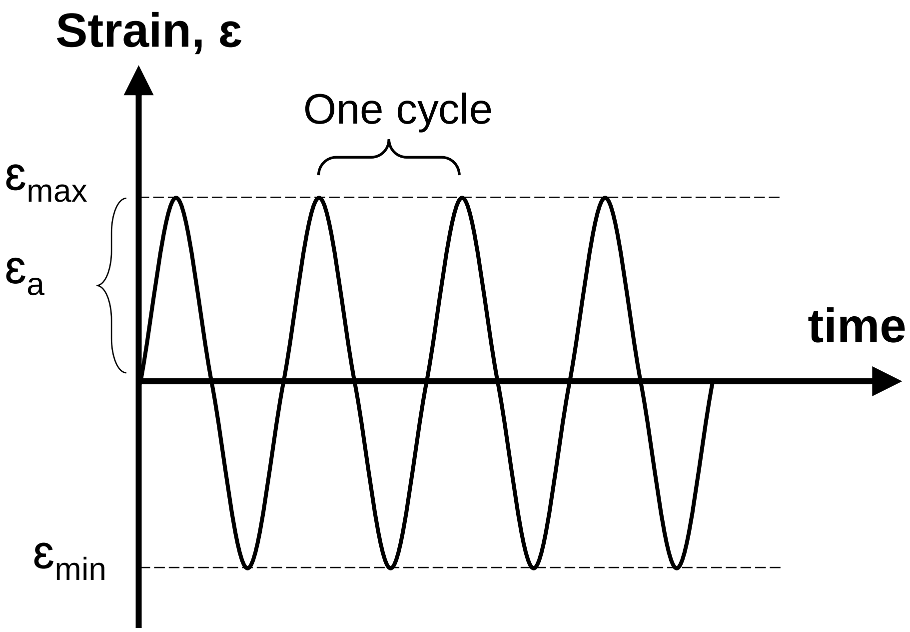
Fatigue stages

- The process until a component finally fails under repeated loading can be divided into three stages:

1. During a large number of cycles, the damage develops on the microscopic level and grows until a macroscopic crack is formed.
2. The macroscopic crack grows in each cycle until it reaches a critical length.
3. The cracked component breaks because it can no longer sustain the peak load.



Cyclic tests



$$\varepsilon_{max} = \varepsilon_m + \varepsilon_a$$

$$\varepsilon_{min} = \varepsilon_m - \varepsilon_a$$

- Strain amplitude:

$$\varepsilon_a = \frac{\varepsilon_{max} - \varepsilon_{min}}{2}$$

- Strain ratio:

$$R = \frac{\varepsilon_{min}}{\varepsilon_{max}}$$

- Mean strain:

$$\varepsilon_m = \frac{\varepsilon_{max} + \varepsilon_{min}}{2}$$

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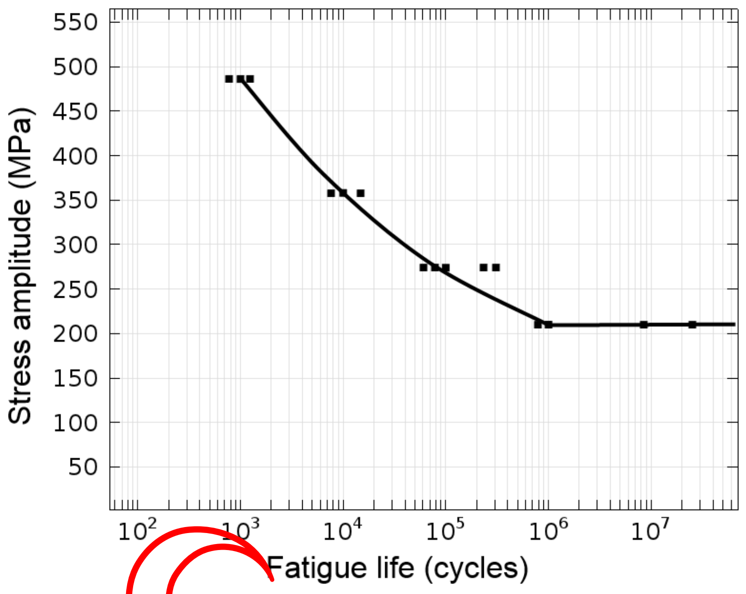
Fatigue models

- Research on fatigue began in the 19th century and led to a number of methods for fatigue prediction.
- Two of the classical models are the Stress-life (S-N) and Strain-life (ε-N) methods.
- Some materials exhibit a stress threshold in fatigue testing known as the endurance limit.
- Below this limit, no fatigue damage is observed, and components can operate for an infinite lifetime.
- Not all materials have an endurance limit. Therefore, they can fail due to fatigue even at low levels of stress.



Fatigue life (N): Total number of cycles leading to final fracture at a given stress/strain.

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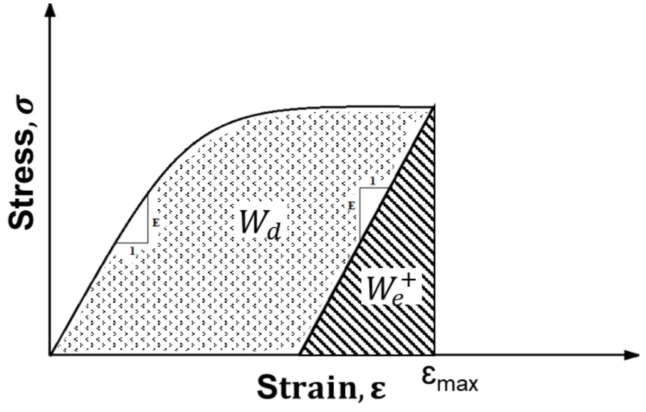
Total fatigue toughness method

- Cumulative energy-based damage parameter
- Capable of predicting the fatigue life based on:
  - ➢Material properties (modulus of elasticity)
  - ➢Loading conditions (strain ratio and mean strain)
- Advantage: One set of experiments will be sufficient to provide a fatigue model.



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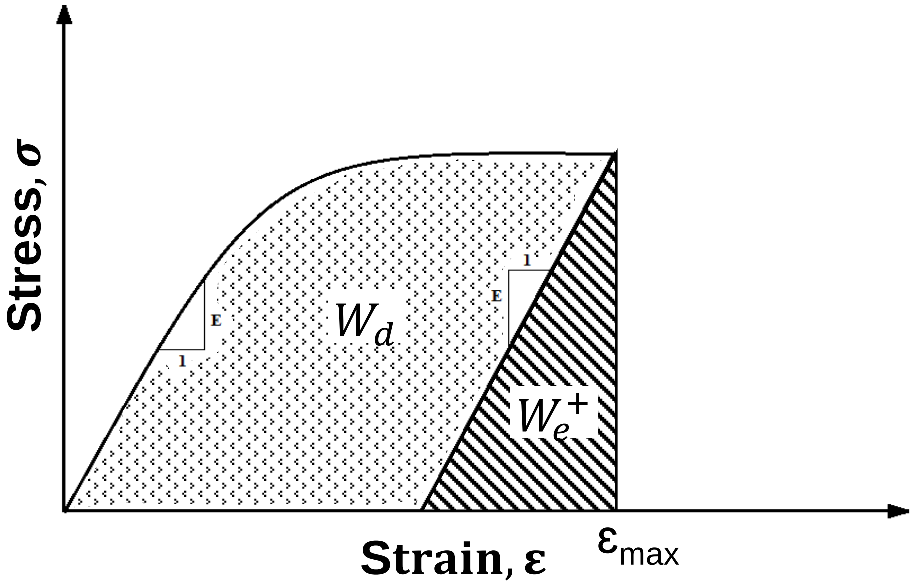
Total fatigue toughness method

- *ΣW_t is called the total fatigue toughness which is cumulative total strain energy density.*
- W_t is the total strain-energy-density.
- W_d is the dissipated strain-energy-density, which is calculated as the area encompassed by the loading and unloading paths.
- W_e^+ is the tensile elastic strain-energy-density that is defined as the area of the triangle generated by linear elastic unloading of the material.



$$\Sigma W_t = \Sigma_i^{N_f} (W_d + W_e^+)_i$$

$$W_t = W_d + W_e^+$$

$$W_e^+ = \frac{\sigma_{max}^2}{2E}$$

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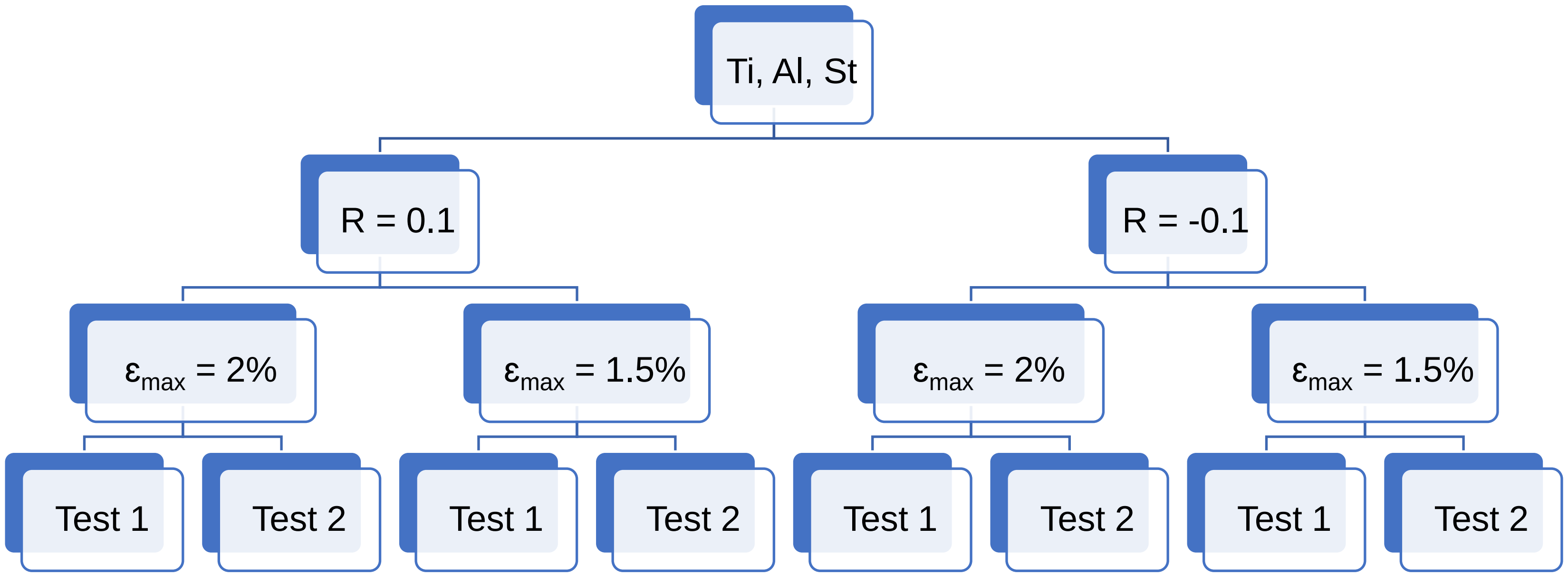
Experimental cyclic tests

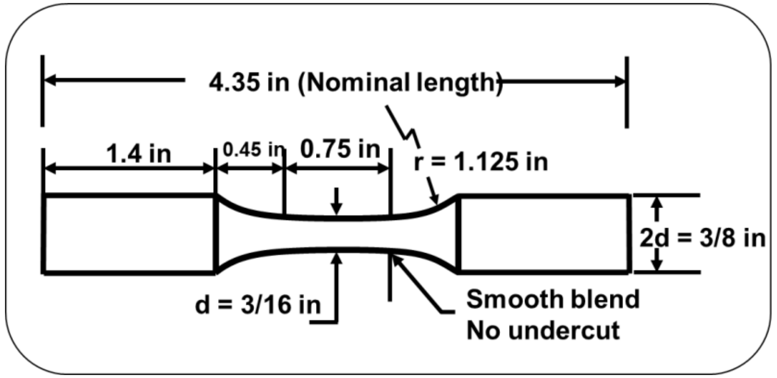
- Materials:
  - ➢ Ti-6Al-4V (titanium alloy)
  - ➢ Aluminum 7075
  - ➢ Steel 4140

- Strain-controlled low-cycle tests.
- Strain ratio, $R = \frac{\varepsilon_{min}}{\varepsilon_{max}}$: R = 0.1, -0.1
- Maximum strain: ε_{max} = 2%, 1.5%



Experimental cyclic tests

- Specimens were designed based on ASTM E606 for fatigue testing.
- All the specimens were cut and machined from metal rods.
- To avoid any stress concentration, the specimens were sanded by sandpapers up to 3000 grit.



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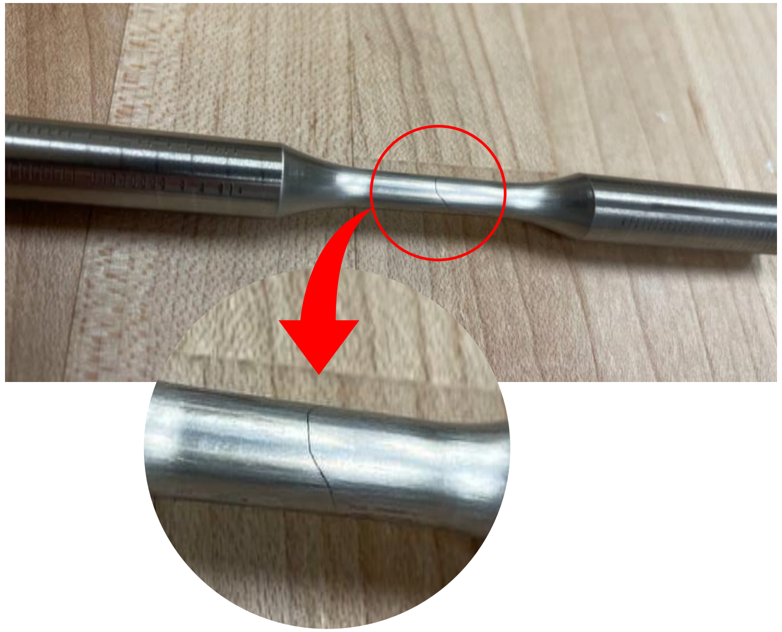
Test results

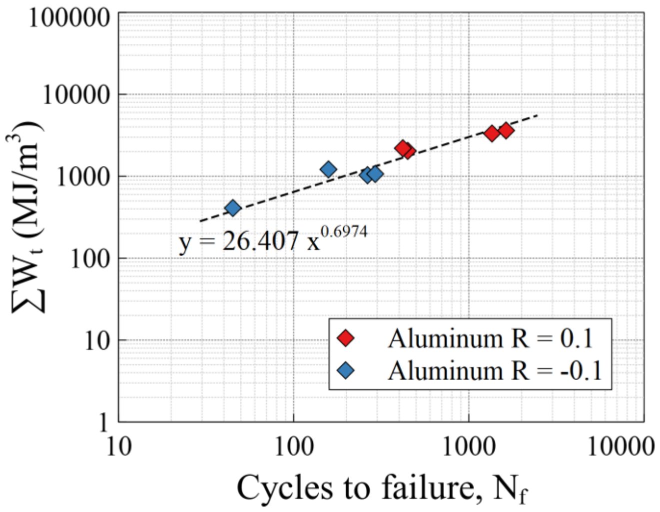
- In a few specimens, the growth of the crack was visible, while in most of them, the specimen broke suddenly.

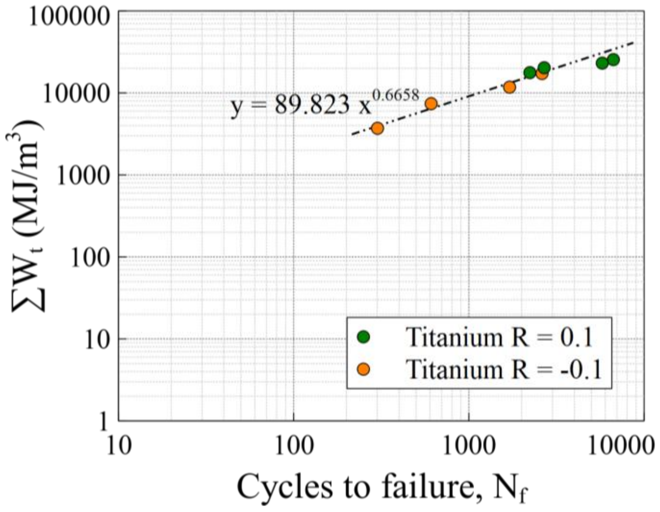
- Proper limits were set in the testing machine to prevent the fracture surfaces from touching each other, and to avoid any damage to extensometer.

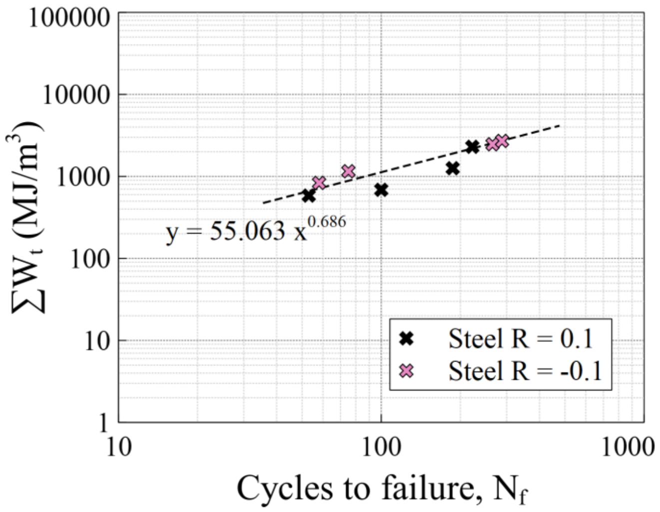


Test results

- Postprocessing was performed using Python.
- Linear relationship between the total fatigue toughness and the fatigue life in the log–log scale, were observed in all materials.







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Conclusions

- Applicability of the total fatigue toughness method for fatigue modeling of Ti-6Al-4V, Aluminum 7075, Steel 4140, were confirmed by conducting Strain-controlled cyclic tests.
- The results showed that this energy-based damage parameter can closely correlate the experimental fatigue datapoints obtained under any loading condition.
- It was found that a set of fatigue tests on any material covering a proper range of fatigue lives can be used to determine the slope and intercept of the prediction line.
- To obtain prediction line, there will not be a need for extreme loading conditions. This helps to avoid buckling and other undesired factors that affect fatigue data.
- This approach can be significantly cost- and time-effective, since by a set of short low-cycle tests, the fatigue life at high cycles can be predicted.

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Thank you!

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