STATUS OF THE FATIGUE STUDIES OF THE CLIC ACCELERATING STRUCTURES
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Quick repeat of the classical fatigue phenomena
Fatigue

- Occurs when a material experiences lengthy periods of cyclic or repeated stresses
- Failure at stress levels much lower than under static loading
- Fatigue is estimated to be responsible for approximately 90% of all metallic failures
- Failure occurs rapidly and without warning
- There is no fixed ratio between materials Yield- and Fatigue Strength
- Normally the ratio varies between 30-60%
- Fatigue Strengths are usually average values
  - Failure is essentially probabilistic. The number of cycles required for failure varies between homogeneous material samples.
  - The greater the applied stress, the shorter the life.
  - Damage is cumulative. Materials do not recover when rested.
Normally, the stress-strain curve of a material shows an elastic region, followed by a strain hardening region, and finally a plastic region. The yield strength ($\sigma_y$) is the stress at which permanent deformation begins. The ultimate tensile strength ($\sigma_{ut}$) is the maximum stress the material can withstand. Fatigue is a term applied to non-ferrous metals and alloys (Al, Cu, Ni, etc.). Stress-strain behavior for ferrous metals shows a peak stress at a certain strain, while non-ferrous metals show a continuous strain hardening.

Fatigue life is the number of cycles at a constant stress level to failure.
This is the page from the MIL-SPEC handbook that was used for the statistical analysis of the scatter in fatigue test data.

The analytical model assumes that all test data regardless of R can be plotted as a straight line on a log-log plot after all the data points are corrected for R.

The biggest problem with this data presentation style is that the trend lines represent 50% confidence at a given life and we need >95% confidence of ability to reach $200 \times 10^6$ cycles.
• This graph plots 55 MIL-SPEC data points corrected for R by the equation at bottom. The y axis is number of cycles to failure, the x axis is equivalent stress in ksi.

• From this graph we concluded that the equivalent stress for >97.5% confidence at $2 \times 10^8$ cycles was 10 ksi.
Things that have an effect on fatigue strength

- Grain size
- Corrosion
- Frequency
- Vacuum
- The Average Mean Stress

- Surface roughness
- Cold-Working
- Thermal treatment
- Operating temperature
- Alloying

For example, shot peening puts the surface in a state of compressive stress which inhibits crack formation thus improving fatigue life.
CLIC fatigue issues
Simulated surface heating of HDS140 structure in Copper Zirconium C15000

Surface heating during 68 ns pulse

Surface cooling between the pulses
(Idle time 6.7 ms)
Max Temperature- and Stress profiles of 68 ns pulse

- Fully compressive cyclic stress condition
- Cyclic peak-to-peak stress 155 MPa
- Cyclic Stress Amplitude 77.5 MPa
CLIC number of cycles:
Repetition rate 150 Hz
Estimated lifetime 20 years
9 months / year
7 days / week
24 hours / day
Total N \(7 \times 10^{10}\)

Stress

\begin{align*}
\text{Mean stress} &\quad -77.5 \text{ MPa} \\
\text{68 ns} &\quad 6.7 \text{ ms} \\
(+)195 \text{ MPa} &\quad 77.5 \text{ MPa}
\end{align*}
Copper alloys are non-ferrous metals

- High criteria of failure due to surface currents. Already a small change in surface roughness is crucial.

- Possible joining method, HIP, softens the material (CuZr)

- Extremely high number of cycles

- Extremely high number of parts, the probability of a failure arises

- The “RF-fatigue” lifetime is difficult to test.
What could be done:

- Select a good material
  - CuZr, GlidCop, CuCrZr...
- Develop other joining method than HIPping
  - Explosion Bonding...
- Hope that the HIPped material (CuZr) is still good enough
  - Will be shown by the near future tests
- Select a material that doesn't soften during HIPping
  - GlidCop...
- Strengthen the material (CuZr) after HIPping
  - CIP
  - Explosion hardening
  - Cavitation Shot-less Peening
Cavitation Shot-less Peening

- Surface hardening of HIPped material
- Compressive residual stress
- Good surface roughness could be preserved
- Tests in collaboration with Tohoku University (Japan) under way
Normalized maximum magnetic field calculated from the best fatigue strength values found from the literature up to $10^8$ cycles [Cu-OFE = 1]
Introduction to Ultrasound fatigue testing
Cyclic mechanical stressing of material at frequency of 24 kHz.

High cycle fatigue data within a reasonable testing time. CLIC lifetime $7 \times 10^{10}$ cycles in 30 days.

Will be used to extend the laser fatigue data up to high cycle region.

Tests for Cu-OFE, CuZr, CuCr$1Zr$ & GlidCop Al-15 under way.
Simulated sonotrode vibration
The operating frequency of the Ultrasound unit is 24 kHz ± 1 kHz.

A crack changes the resonant frequency of the sample.

When the crack is about 2 mm deep, the sample is 1 kHz off the resonance and the device stops the "normal" operation.

Material characterization at same time
Diamond turned specimen before

After 3*10^6 cycles at stress amplitude 200 MPa
Status report
Copper, Dubna RF-fatigue test
Annealed Copper, SLAC RF-fatigue test, Pritzkau
Annealed Copper, SLAC RF-fatigue test, Pritzkau
- The 40% Cold Worked CuZr sample survived the CLIC lifetime without a crack.

- Something happened on the surface already around $10^{10}$ cycles.

- If the surface roughness is increased, this could be dangerous for the RF induced fatigue.
Future Plans, Ultrasound tests
• Complete the fatigue data for Cu-OFE and CuCrZr

• Perform fatigue tests for Copper Zirconium at different states
  • “as HIPped” -state
  • Surface hardened by Shot Peening
  • High ratio of Cold Working (80%)

• Investigate the surface effects during the mechanical cyclic loading.

• Vary the stress condition (next slide)
Varying the stress condition by a special pre-stressed specimen

Titanium body
Copper alloy specimen
Titanium nut

Introduction of a compressive pre-stress

Standard ultrasound stress condition

σ(t)

Pulsating compression stress

Pulsating reversed stress

σ_max = 0

σ_m = 0

σ_m

σ_a

σ_m

σ_a
Looks like the two (laser and ultrasound) methods can be connected and the total CLIC lifetime be predicted.

The calibration with RF fatigue experiment is needed!

The up-to-date results shows that the CLIC structures could perhaps be based on even an existing material without reducing the target parameters.

The material should be from the group of High Conductivity Copper Alloys (Lower conductivity -> Higher Stress).

More attention must be paid on the high cycle surface effects during the Ultrasound experiment. Could be crucial for RF.

The fatigue data for the same materials at different states should be collected, especially at “soft” states.

The High Cycle fatigue behavior at different stress conditions should be tested.

Perform more data for statistics.
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