Temperature-Dependent Evolution of the Cyclic Yield Stress of Railway Wheel Steels

Johan Ahlström, Elena Kabo and Anders Ekberg
CHARMEC
(Chalmers Railway Mechanics)
Chalmers
University of Technology, Sweden

10th International Conference on Contact Mechanics
August 30, 2015 - September 3, 2015 | Colorado Springs, Colorado, USA
• Aim: Improve description of material characteristics in RCF analysis
• Experiments and evaluation of test results:
  – Influence of strain amplitude, temperature and hold times on cyclic yield stress
  – Approach for identification of cyclic yield stress from loop data
• Improved RCF criterion
• Conclusions and future work
Background and aim

- Current evaluation scheme ("shakedown map") based on \( k \), the yield limit in shear

- From LCF studies a cyclic yield stress can be determined:
  - previous load cycles (hardening / softening)
  - overloads
  - temperature (including history, hold periods) etc

- Aim towards RCF criterion with more representative material description
Tests + compensation for micro-plastic strains

Strain control, $R_\varepsilon = -1$, 
$\Delta \varepsilon/2$: 0.4, 0.6 and 1.0 %,  
$\partial \varepsilon / \partial t = 5 \cdot 10^{-3}$ s$^{-1}$,  
Different temperatures, hold periods

1. Fitting unloading curves to 2$^{nd}$ order polynomial

2. Removing elastic strains on compressive and tensile sides
"Offset" cyclic yield stress

2 x Cyclic yield stress
Cyclic yield stress @ different temperatures

Material: R7T
\[ \Delta\varepsilon_t / 2 = 0.6\% \]

- 20°C
- 300°C
- 500°C
- 600°C

Flow Stress Development [MPa]

\[ N/N_f \]
Cyclic yield stress, temperature range 250–400°C

Dynamic strain ageing (dislocation locking) vs thermal activation of dislocations
The influence of total strain amplitude at elevated temperatures
Stress relaxation during hold time – small viscous behaviour

250C06WR7T23, Stress relaxation during static hold

250°C

-300
-350
-400
-450
-500
-550
-600
0 1 2 3 4 5 6 7 8

Time (h)

Stress (MPa)

thermal+mech strain
mech strain
fit to thermal+mech
Number of cycles to failure, $N_f$

$\Delta \varepsilon_t/2 = 1.0\%$

$\Delta \varepsilon_t/2 = 0.6\%$

$\Delta \varepsilon_t/2 = 0.4\%$
Conclusions on material characteristics

• Strong influence of temperature on cyclic yield stress! Approximate hardening or softening @ $N_f/2$ (compared to 20°C):
  - 300°C $\rightarrow$ 30% ↗ (Dynamic strain ageing dominates)
  - 500°C $\rightarrow$ 30% ↘ (Thermal activation of dislocations)
  - 600°C $\rightarrow$ 60% ↘ (Thermal activation of dislocations + microstructure degradation)

• Major effect of temperature for $T > 250$ °C

• Hold periods have little influence on cyclic yield stress and probably limited effect on $N_f$. 
Fatigue damage model

Fatigue index for surface initiated RCF

- based on Johnson’s shakedown map
- indicates surface plasticity
- $\mu, a, b, F_z$ – output from dynamic simulations

\[
FI_{surf} = \mu - \frac{2\pi abk}{3F_z}
\]

\[
\frac{1}{N_f} = D \approx \left(\frac{FI_{surf}}{10}\right)^4 \quad \forall FI_{surf} \geq 0
\]

- $D$ – damage corresponding to one load cycle
- $N_f$ – fatigue life
Cyclic yield stress in shear $k$

\[
D \approx \left( \frac{F l_{\text{surf}}}{10} \right)^4 \quad F l_{\text{surf}} = \mu - \frac{2\pi abk}{3F_z}
\]

- Commonly taken as $k \approx 300$ MPa
- In reality

\[
k = k(T, N, \ldots)
\]

- $T$ – operational temperature
  - can have major influence
- $N$ – number of applied load cycles
  - influence of $N/N_f$, but $N_f$ is not known beforehand

Experiments on R7T wheel material
Proposed estimation of cyclic yield stress $k$

Based on experiments on R7T wheel material:

- Temperature dependent for $T > 250 \, ^\circ\text{C}$
- Estimated average of $k$ over the fatigue life employed (mainly effect for $250 < T < 300 \, ^\circ\text{C}$)
- Values corresponding to 0.6% (total strain amplitude) are employed

$k = 300 \, \text{MPa} \quad \forall T, 20 \, ^\circ\text{C} \leq T \leq 250 \, ^\circ\text{C}$

- 3$\text{rd}$ degree polynomial trend:

$$k = 2.0 \times 10^{-5} T^3 - 0.0217 T^2 + 9.372 T - 919.34 \quad \forall T, 250 \, ^\circ\text{C} < T \leq 600 \, ^\circ\text{C}$$
Conclusions on RCF analysis and future work

• Temperature has a major effect – a temperature dependent $k$ value has been derived

• $k$ is a function of $N / N_f$ for temperatures $T=250$ and $T=300°C$. This history effect is not included since $N_f$ is unknown (non-constant load)

• Experimentally examined strain amplitudes have shown major effect at lower temperatures but not yet included in the criterion

• Strain rate is not included so far.
  • Partly examined by relaxation during hold periods
  • Further experimental data required to quantify the effect and determine when it needs to be considered
Thank you for your kind attention!