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Industry Trends in Fatigue Testing of Rubber Reinforcement Materials

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Outline

1. bogimac MFTE
2. Rubber Reinforcement Materials
3. Fatigue Failure
   a) Failure Modes
   b) EOL/HCF/MCF/LCF cycle load/count conditions
4. Fatigue Test Basics
5. Test Workflows
6. MFT Equipment for tire & rubber reinforcement
   a) Tensile > CTC, LHC
   b) Bend-Rotation > BRH, BRS
   c) Bend-over-Sheave Shoeshine test > BSC
   d) Preparation of reinforced rubber > VPB/VMH/VCD
   e) Impact > IUS > IPS
7. MFTE underlying Technology
Fast material fatigue validation, in the early stage of the design, relevant to real usage conditions, maximising on test expertise

DNA: weaving machine
- 24h/7d/52w/7y
- high speed, big stroke & load
- uptodate mecha-tron-it techno
- industry generic machine design
- variant to final customer need

Industries
Rubber & reinforcement
Flexible cable
Conveyor belt
Textile cord & rope
Hoses & reinforcement
Medical wire & cord
Tire reinforcement
Superabrasives
Transmission belt
Steel wire, cord & rope

MFTE References
Bekaert (BE, CL, CN, IN, SK)
Bosch SIA Abrasives (CH)
Bridgestone (JP, USA)
Bridon (BE)
Contitech (DE, USA)
Diarotech (BE)
Dupont de Nemours (CH)
Dunlop Aircraft (UK)
Fordia (CA)
Glanzstoff (LU)
Goodyear (LU, USA)
Halliburton (USA)
Husqvarna (BE, CN)
Kiswire (CZ)
Kordsa (TR)
Michelin (FR)
Milliken (USA)
MRF Tyres (IN)
Nokian Tyres (FI)
Optibelt (DE, IR)
Semperit (AT)
Teijin (NL)
Xingda (CN)
2. Rubber Reinforcement Materials

eg: Tire reinforcement material usage in 2013 (Kton worldwide)

(*) data from TTX-2015 ‘Introduction to Tire Reinforcement Materials’

<table>
<thead>
<tr>
<th>Material</th>
<th>Usage (Kton)</th>
</tr>
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<tbody>
<tr>
<td>Steel</td>
<td>4580</td>
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<tr>
<td>Aramid</td>
<td>6</td>
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<tr>
<td>Rayon</td>
<td>50</td>
</tr>
<tr>
<td>Polyester</td>
<td>730</td>
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<tr>
<td>Nylon</td>
<td>950</td>
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</tbody>
</table>
### Material specification (*)

<table>
<thead>
<tr>
<th>Drawn Material</th>
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<tbody>
<tr>
<td>Ro (Density) kg/m³</td>
</tr>
<tr>
<td>steel</td>
</tr>
<tr>
<td>aramid</td>
</tr>
<tr>
<td>rayon</td>
</tr>
<tr>
<td>polyester HMLS</td>
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<tr>
<td>polyester</td>
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<tr>
<td>nylon</td>
</tr>
<tr>
<td>carbon</td>
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<tr>
<td>glass</td>
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</table>

1 tex=1gr/1000m  TS=Ro*Tenacity  E=Ro*SpecialModulus  dia=sqrt((4*tex)/(pi*ro))

(*) Original data from TTX-2015 ‘Introduction to Tire Reinforcement Materials, reworked’
Steel wire & cord

![Steel wire & cord image]

- 2×1
- 2+2
- 3×1 OC
- 3×1 Betru
- 5×1 Betru

**Tensile strength of steelcord filaments**

![Tensile strength graph]

"Material Fatigue Testing Equipment for Rubber Reinforcement Materials"
Rayon, PEN, PET HMLS, PET, PA6-6, PA6
Aramide & hybrids

"Material Fatigue Testing Equipment for Rubber Reinforcement Materials"

copyright bogimac
Usage of new higher grades to be validated

eg: Trend to higher wire grades on steel cord for tire, belt & hose
    NT > HT > ST > UT

eg: PA PES grades
eg: multilayer PA
    > dual layer Ar/PA hybrid

> fulfill high durability requirements
  (eg: Timing belt ~ 600 MC)
  (eg: Truck/Bus Tire = 400 MC, re-tread)
> lower number of reinforcement layers
> smaller wire & cord diameter
> higher flexibility
> less SC-rubber composite thickness > lower material cost
> lower rolling resistance (lower energy cost & CO2-emission)
  - less reinforcement layers > less rubber thickness
  - higher wire strength > smaller more flexible wire diameter
> compact design of transmission
> high impact strength
Trend away from “over-engineered” usage

> Cost
- lighter material usage, using them closer to their (new validated) limits
- improve & sensibilise on total cost of ownership, including services
- tune: not for "best" but for "right" quality, evtl by different branding

> Lower application losses
- on rubber & reinforcement lower the hysteris losses
- less, thinner & more flexible layers, thanks to better knowledge of existing grade & introduction of new or higher grade (not limitative "strength") materials

> Improve rubber adhesion
  to compensate smaller interface surfaces and higher load on the materials

> Improve on impact & puncture resistance

> Environmental: ECO, REACH, CO2 footprint, re-use, bio-material

Materials need to be used up to secure LCF/MCF/HCF limit
Validate early the materials to those limits, as assumed in design

OLD ASTM & other test norms at static & LCF are not anymore relevant enough for the challenges of MODERN TIRE DESIGN

"Material Fatigue Testing Equipment for Rubber Reinforcement Materials"
Material failure is initiated in many different ways, that have to be considered specifically, depending on:

> Industry application: tire, conveyor belt, transmission belt, hose, bladder, ...
> Specific product performance: load, speed, durability, security
> Region specifics: climatic, usage, care
> Reinforcement material & construction: steel & textile

For each failure mode eventually, one has to consider different cycle load/cycle levels (*):

- **HCF** (High Cycle Fatigue ~ 50 - 200 MC)<br>  
  on nominal loads
- **MCF** (Medium Cycle Fatigue ~ 100kC - 10 MC)<br>  
  on Impact & Run-Flat load conditions
- **LCF** (Low Cycle Fatigue ~ 1C - 10 kC)<br>  
  during Mfg and "extreme" over-loading
- **CREEP & AGING** being long term degrading cycle of the mechanical properties

(*) In rubber reinforcement applications, even metallic steel wire & especially steel cord have no FL (Fatigue Limit, eg evaluated at 10^7 cycles for steel itself), because of fatigue issues on fretting & dynamic rubber adhesion.
## 3a) Failure modes in reinforced rubber

<table>
<thead>
<tr>
<th>Mode</th>
<th>Description</th>
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<tr>
<td><strong>Uniaxial load</strong></td>
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<tr>
<td>Tension-tension</td>
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<tr>
<td>Dynamic compression</td>
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<tr>
<td><strong>Bending</strong></td>
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<td>Bending stress</td>
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<td>Fretting</td>
<td></td>
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<tr>
<td><strong>Delamination</strong></td>
<td></td>
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<tr>
<td>Shear in rubber matrix</td>
<td></td>
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<tr>
<td>Dynamic Adhesion</td>
<td></td>
</tr>
<tr>
<td>Cord Crack initiation</td>
<td></td>
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<tr>
<td><strong>Impact &amp; Puncture</strong></td>
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</tbody>
</table>
Uniaxial Load

> TENSION-TENSION
- one-way alternating tension (cap ply, carcass sidewall)

> TENSION-COMPRESSION (belt, carcass shoulder & apex):
- reverse alternating tension-compression
- dynamic compression on lower layers of dual- or multi-layer bend

- risk of bird cage compression yielding under extreme loads
Single & Reverse Bending

> BENDING

bending stress in fil/wire: \( \sigma_{\text{fil}} = 2 \times E \times \left( \frac{d_{\text{fil}}}{R_{\text{bend}}} \right) \)

- **SC wire**  \( d_{\text{fil}} = 0.15 \sim 0.45 \text{ mm} \)  \( E = 200000 \text{ MPa} \)
  (TC filament  \( d_{\text{fil}} \sim 0.012 \text{ mm} \)  \( E = 3000-80000 \text{ MPa} \))
- one-way pulse bending (belt mid & cap ply)
- reverse bending of cord (carcass at shoulder & apex)

fretting

- intra-ply filament fibrillation fatigue in cord
- inter-ply textile or steel wire fretting
  in cord when no full rubber penetration
Shear fatigue, dynamic Adhesion & Delamination

> **DYNAMIC ADHESION**

x delamination at cord
- inter-ply in textile cord
- inter-wire in steel cord
- cord-rubber adhesion by:
  (belt layer angle shift)
  (fast crack bridging on too short spacing)
  (inter-layer shear during bending)
  (crack initiation by cord dynamic compression)
also depending on cord twist, cord rivet & rubber gauge

x delamination of the rubber
  on compound fatigue shear
  as seen on nearly full cord rubber coverage

x delamination on inter-belt-plie, mainly at shoulder
  - from overheating on over-loading, under- or over-inflation

x delamination between tread & belt layer
Crack initiation & propagation up to failure
Impact & Puncture

> IMPACT & PUNCTURE

[Images of tire damage and puncture marks]
Aging & Creep

> AGING

- temperature from curing
- ambiant climatic condition
- product heatup
- oxidation
- penetrating humidity affecting textile dipping & brass steel cord on rubber adhesion
- chemical interaction reaction between compound, dipping, reinforcement
- salt water corrosion
- UV light, ozon on compound

> CREEP (= aging on elongation under constant load)
3b) Failure Modes test at different load/cycle cases

- **normal usage @ HCF**
  - single & reverse bending
  - intra-cord wire or fibre fretting
  - tension-tension
  - intra-cord adhesion
  - dynamic adhesion
  - rubber shear

- **occasional load @ MCF**
  - tension-compression
  - small impact & puncture

- **critical failure @ LCF**
  - bird-caging by compression
  - heavy impact & puncture
The small woodpecker also knows how to „fatigue-drill“ wood materials by hitting many times at high „machine gun“ frequency (... without getting headaches)
Static ultimate test <vs> ...

> Static break test by plastic deformation or brittle failure, mostly done only once (1) up to failure at low predefined strain rate.

- Tensile Strength > force-elongation
- Torsion count numbering > torsion-rotation
- Peel adhesion

> Used for uni-axial stress-strain material characterisation
but not any more relevant on its own for final differentiation

**Metal**: steel wires with the same UTS static breaking strength can give totally different bending fatigue cycle counts

eg 1/20, as observed on the bend-rotation test method
(bend rotation test @ 900 MPa for same UTS : 20kC<>400kC)

**Textile**: fibre cord dipping with high static rubber adhesion could because of its higher latex stiffness be worser on remaining peel strength after fatigue

eg static peel test, after 10^6 cycles degradation (dual layer reinforced rubber on the bend-over-sheave test method)
... in real usage mostly fatigue failure

Wire surface oxidation, inclusion, damage, metallurgic brittleness, residual stress, brass aging, corrosion
Thermal degradation by internal work heating
Combined stress conditions & uneven tension
Inter/intra cord fretting by bending under tension
Fibre & cord dynamic compression to macro & micro buckling
Crack inhibition & crack growth
on inclusion or local delamination
Degradation of rubber & adhesion
on brass coating or RFL dipping
by bending, shear, temperature,
saltwater, humidity, contaminant,
UV, ozon

> fatigue failure behaviour
different from static failure

"Material Fatigue Testing Equipment for Rubber Reinforcement Materials"
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Cycle count, stress average & amplitude curves

Stress-Cycle Count curve
> Wohler S-N curve

Stress Mean & Amplitude for specific cycle count
> Smith-Goodmann (or Haig-Soderberg) diagram
Fatigue test must be relevant to “real usage”

The static test is the worst case of sample overloading for fast results.

Beware of overloading, thereby probably excluding the materials & constructions that you really need.

Be sure to stay at the right side of the cross-region of the new curves.

Re-validate cycle & load at every new paradigm.

1) run up to full failure
2) runout & static remaining strength
3) run up to partial failure (EW)
Tire & rubber reinforcement failure is initiated in many different ways, that need to be considered, each with its related fatigue cycle count.

**UFL** (Under Fatigue Life test load) always **EOL**

In tire & rubber reinforcement applications,
even steel wire & especially steel cord
have no FL (Fatigue Life limit, eg for steel evaluated at $10^7$ cycles)
because of fatigue issues on fretting & dynamic rubber adhesion

**HCF** (High Cycle Fatigue ~100-400 MC)
on nominal loads

**MCF** (Medium Cycle Fatigue 100kC ~10 MC)
on "occasionally" occurring Impact & Run-Flat load conditions

**LCF** (Low Cycle Fatigue 1C ~ 10 kC)
during Mfg and "extreme" over-loading, puncture, over- or under-inflation

**AGING**
= 1 single long term degrading cycle of the material & mechanical properties

**CREEP**
= aging by elongation under load & environment conditions
Beware on "overloading for fast results"

As in the case of single shot UTS test, with an overloaded test eventually the small defect, that after crack initiation & propagation is affecting the fatigue cycle count, will even not initiate a crack before the sample failure.
Higher quality & grades = higher fatigue cycling

To differentiate correctly higher quality materials one needs to run fatigue testing at lower stresses well below Fb/3 for higher cycle counts.

<table>
<thead>
<tr>
<th>Material</th>
<th>Quality</th>
<th>Tensile Strength (GPa)</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static test</td>
<td>UTS</td>
<td>1.0</td>
<td>1 Cycle</td>
</tr>
<tr>
<td>Quasi-static (plastic)</td>
<td>low Q</td>
<td>1.5</td>
<td>n x 1-100 kC</td>
</tr>
<tr>
<td></td>
<td>standard</td>
<td>1.9</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>high Q</td>
<td>2.4</td>
<td>~ usage Fb/12-Fb/8</td>
</tr>
<tr>
<td>Wirerope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NT</td>
<td>~ 10-200 MCycle</td>
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<tr>
<td></td>
<td>HT</td>
<td>~ 100 kC</td>
<td></td>
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<tr>
<td></td>
<td>ST</td>
<td>...</td>
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</tr>
<tr>
<td></td>
<td>UT</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Steelcord</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>extreme Q</td>
<td>1 GCycle</td>
<td></td>
</tr>
<tr>
<td>Medical/Aero/Space</td>
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</tbody>
</table>
New test paradigm thanks to & for FEA simulation.
From Relative to Absolute test (FEA of test case)
4. Fatigue Test Workflows

> Test up to "runout" cycle count without failure
  = define security factor on LCF/MCF/HCF/LF "runout" cycle-count load case
  & do the static test after this runout for Remaining UTS/Peel Strength

> Full characterisation:
  load vs cycle-count & deviation
  = test up to failure for full Whöler curve

> Test for failure at startup load condition
  - when stop at failure, next on step-down load
  - stop at runout, next at step-up load
  = Faster result to define maximum permissible load
  for LCF/MCF/HCF/LF cycle count case
  Mood Dillon stair-case method (& bogimac variant)

> Observation of the beginning of the failure to "know why"
  = run up to Early Warning Stop

> Test up to failure & make extensive analysis at the failure region
  wire: microscopy, microspectrometallurgic analysis on failure of bend-rotation (BRS)
  wirerod: standard metallurgic analysis on failure of dynamic tension (LHC)
... Wöhler S-N load-cycle failure curve

On tire & rubber reinforcement there is no "infinite life fatigue"
Search for maximum load to reach "runout" cycle count:

> On "runout" decide for next test to step up (survival) or down (failure) the load

> ‘bogimac’ variant possible on fast MFTE: ... but still always run up to failure, to get precise estimation of the deviation on the result
... On failure, beyond statistics, “Know Why”

Know-Why by analysis on microscope, micro-spectrography, ...

- Inclusion
- Surface defect
- Drawing mark
- Oxidation
- Welding spot
- Residual stresses
- Metallurgic segregation
- Overdrawing
- Surface decarburization
... "Early-Warning" stop: observe start of failure
6. MFT Equipment
6a) Tensile testing
LHC-24k8 uni-axial fatigue

Linear Harmonic Stress testing of *wirerod*, wire, textile/wirecord & rope & not axi-symmetric wire, band or strip

- Frequency up to 40 Hz
- Variable stroke eg 0-12 mm
- Force up to 24.800 N
- Tension, Compression & combi mode (T-T, T-C & C-C)
- control for constant Tension or Stroke
- CBS or CSP clamps
- dynaLyse touchpanel PC
- Adaptiv Control
- Early Warning
- Low energy requirement
- Low noise & dynamic foot forces
CBS cord & rope sample clamp

> Application on static UTS, rope stiffness & fatigue failure (see LHC)

> Stiff clamping method differentiates better for uneven tensioning of wire & strand in rope construction

> With interface variants for bogimac LHC, Galdabini, Instron, MTS, Zwick, ...

> external CWD clamping tool
CTC traverse contact clamp

on classic static tensile strength tester
or on dynamic tensile tester

- detection of remaining resilience (e.g., bead wire)
- effect of inter-wire contact (cord, rope, beadwire)

- piccolo (d0.5 mm - F15N)
- soprano (d0.5 mm - F100N)
- alto (d1.5 mm - F1000N)
- basso (d5.5 mm - F14000N)

> traverse angle 15° to 90°
> microcontroller regulation
> clamp vertical suspension
> traverse force
6b) Bend-Rotation (Hunter)
Bend-Rotation fatigue testing

Steel wires of different origins, having identical static UTS values, are giving completely different results on bending fatigue.

eg fatigue bending on Hunter tester
@ 900 MPa
> Brand B  ~ 400,000 cycles
> Brand C  ~ 20,000 cycles
Bend rotation of wire & cord

- High productivity
  - multihead on 5 samples
  - 3000 – 6000 (9000) rpm
- Dry or corrosive dipping, V/H workplane
- SmartControl microprocessor control
- Calculation of test conditions, semi-automatic
- Symmetric operation of the guiding elements
- Special piezo break-sensor break sensor for break detection of the finest wires (< 40 µ), even on corrosive wet dipping conditions
- Easy switch to chuck break-sensor for thicker wires & cords
- Test stop on break, periodic & total cycles
- dynaLyse touchpanel PC HMI
6c) Bend-over-Sheave (Shoeshine)
Fatigue test method for wire, cord, rope & rubber reinforcement on "bending under tension"

Flexible sample on single/reverse bending

Rubber belt sample with single layer reinforcement
  - single bending under tension
  - intra-cord wire & fibre fretting & adhesion
  - reverse bending under tension

Rubber sample with dual layer reinforcement
  - dynamic adhesion
  - dynamic compression of the cord under rubber pressure (inflation)
  - inter-ply delamination
  - rubber shear fatigue
BSC5-3k & BSC2-3k for cord, strip, tape & fabric

cord & single/dual layer reinforced rubber strip tested on single & reverse bending
"Absolute" testing to stress & strain in dual layer
BSC5-3k & BSC2-3k specifications

- cord, single & dual ply samples
- speeds 60-480/720/960/1080 rpm, in func of (# of heads, stroke, load)
- stiff puller force up to 3000 N
- sample width 15/25/(28)(30)(40) mm
- single bending up to D120
- reverse bending up to 3x D80 (D120)
- stroke 40-80 (-120) mm
- [AF] high speed > ambient fan
- [IrT] sample temperature monitoring
- [TH50], [T70] & [RH90] climatics
- [AC] Adaptive Control (F, T, rpm)
- [EW] Early Warning stop (to „know why“)
- dynaLyse application framework
6d) Shoeshine sample preparation
Shoeshine sample preparation

- Plunger mold instead of cavity mold, to ensure that the press force is acting only on the rubber surface area. Peel values are heavily affected by the vulcanisation pressure, that must be precise (*Queen Mary Univ London)
- Much longer samples needed for single bend on big wheel diameters & reverse bending on 3-wheel kit
- Vulcanisation press should also be used for ASTM & other legacy molds
- Precise positioning of the cord in density, with good alignment between upper & dual layer
- Precise interply distance, affecting heavily compression & shear values
- Equal cord tensioning, so that during the fatigue test on the bend-over-sheave all the cords are taking their fair part of the dynamic load
- Cutting of sample strips without cutting unevenly or through cords
VMH "plunger" mold with tensioning frames
VPB-210k desktop vulcanisation press
VCD cutting dies for green rubber & sample
6e) Impact & Puncture
customer specific IUS-300 ultime impact energy

energy profile during single shot impact failure of rubber reinforced samples

(2018-19 > next: IPS-150/300)
coming soon: IPF-300 for LCF/MCF

<< On the tire standardised impact & puncture tests are done for final acceptance, with monitoring of the impact energy absorption, on 1 or low count cycles.

NEXT >> IPS-150/300 for impact & puncture tests under UIS/LCF/MCF of reinforced rubber sample strips.
7. MFTE underlying Technology
<table>
<thead>
<tr>
<th>Climatic Conditioning &amp; Test Monitoring</th>
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<tbody>
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<td><strong>climatic</strong></td>
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<td><strong>monitor</strong></td>
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<tr>
<td><strong>control</strong></td>
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</tbody>
</table>
dynaLyse machine HMI & test application suite

Touchpanel PC HMI
Operator/Tech/Ing
Multi-language
Test receipt management
Data acquisition
Monitor & Log
Graphical presentation
Adaptive control
Early Warning
Automation scripting
Remote diagnostic
Remote software upgrade
Customer onsite calibration
Network & LIMS interface

"Material Fatigue Testing Equipment for Rubber Reinforcement Materials"

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On site machine sensor calibration by customer
val project supplier_A_vs_B
val task dynamic_adhesion
val sample A_ZD34
val testcnt 4
val cfgscript dynadh_1MPa
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