Modeling the rate-dependent inelastic deformation of porous polycrystalline silver films

29th European Symposium on Reliability of Electron Devices, Failure Physics and Analysis

03.10.2018

Sebastian A. Letz
Azin Farooghian
Flaviu B. Simon
Andreas Schletz

Fraunhofer-Institute for Integrated Systems and Device Technology (IISB)
Head: Prof. Dr.-Ing. Martin März

Schottkystr. 10
91058 Erlangen, Germany

Fraunhofer
IISB

Content

- Introduction
- Materials and methods
  - Sample preparation
  - Uniaxial loading experiments
  - General modeling strategy
  - Model parameterization
- Results and discussion
  - Creep experiments
  - Monotonic hardening experiments
  - Multiple-Hardening-Relaxation computations
- Summary, conclusions and next steps

Sebastian Letz, 03.10.2018

Introduction

- Established interconnection material for die attachment in power electronics applications
- Still questions on manufacturing and design for lifetime estimations
  - Some experimental results on time dependence available in literature
  - No detailed discussion about modeling of the results
  - Application: different time and stress domains, complex loading situations
  - Internal porous structure → high internal stresses
- How to model the results for which application?

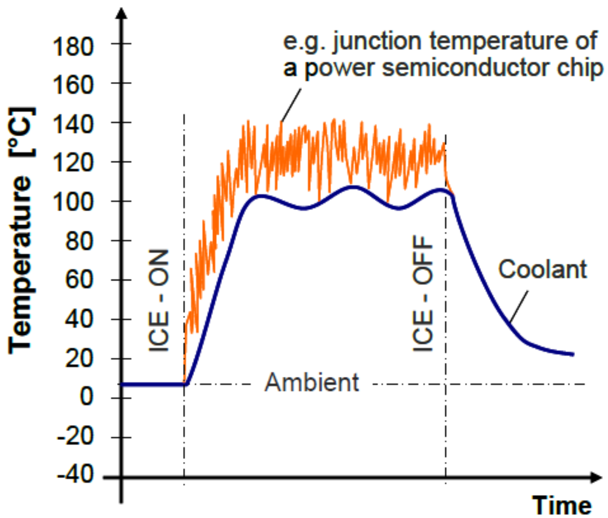

Fig.: Typical semiconductor temperature profile during operation[1].

[1]Ref.: Maerz, M. et al.: Mechatronic Integration into Hybrid Powertrain – The Thermal Challenge, APEConference, 2006

ESREF 2018

Fraunhofer IISB

Materials and methods

- Sample preparation
  - Sinterpaste: Heraeus LTS043
  - Stencil printing of paste on Si substrate
  - Drying at 100°C for 30 min
  - Sintering in hot uniaxial-press
    - Temperature: 250°C
    - Time: 120 s
    - Pressure: 20 MPa
  - Laser cutting to dog bone shape
  - Final sample thickness: ca. 40 µm

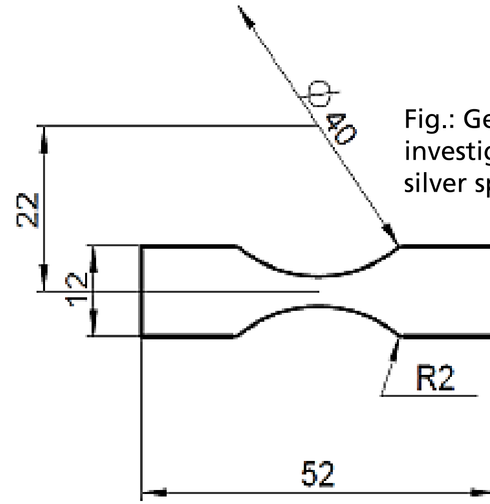

Fig.: Geometry of the investigated sintered silver specimens.

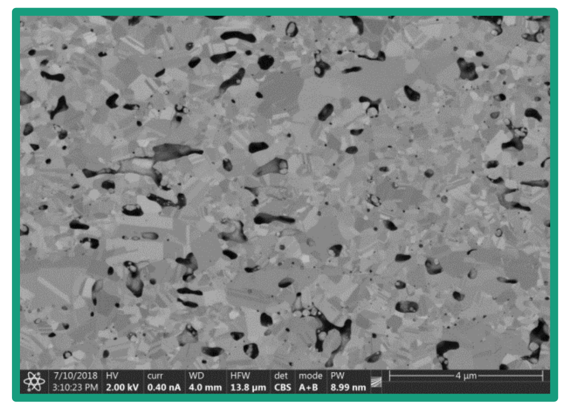

Fig.: FIB-Cross section showing the microstructure of the investigated sintered silver specimens.

Materials and methods

- Uniaxial loading experiments
  - Lloyd testing machine equipped with temperature chamber
  - Strain measurement: Limess Digital-Image-Correlation system

  - Monotonic hardening
    - Constant cross head speed
    - Temp.: 25°C, 150°C, 250°C
  - Creep loading
    - Const. load: 10 N, 12.5N, 15N
    - Temp.: 75°C, 125°C, 125°C

Fig.: Setup for monotonic hardening and creep loading experiments.

Materials and methods

- General modeling strategy: Basic equations and assumptions

  - Decomposition of total strain (small strain theory)

$$\boldsymbol{\varepsilon_{tot}} = \boldsymbol{\varepsilon_e} + \boldsymbol{\varepsilon_p} + \boldsymbol{\varepsilon_{vp}} = \boldsymbol{\varepsilon_e} + \boldsymbol{\varepsilon_{in}}$$

  - Stress depends only on plastic strain and plastic strain rate

$$\boldsymbol{\sigma} = f\left(\boldsymbol{\varepsilon_p}, \dot{\boldsymbol{\varepsilon}}_{\boldsymbol{p}}\right)$$

  - Elastic strain: Linear isotropic thermo-elasticity law

$$\boldsymbol{\varepsilon_e} = \frac{1+\upsilon}{E}\boldsymbol{\sigma} - \frac{\upsilon}{E}Tr(\boldsymbol{\sigma})\mathbf{1} + \alpha\Theta\mathbf{1}$$

Materials and methods

- General modeling strategy: Plasticity computation

Plastic strain by associative flow rule	$\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{p}} = \dot{\lambda}\left(\frac{\partial f}{\partial \boldsymbol{\sigma}}\right)$
Evolution of v. Mises yield surface by flow function	$f = J_2(\boldsymbol{\sigma}) - R = 0$
Isotropic scalar hardening variable (Thermodynamic force)	$R = \rho\left(\frac{\partial \Psi}{\partial p}\right) = k(p)$
Accumulated plastic strain definition	$\dot{p} = \sqrt{\left(\frac{2}{3}\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{p}} : \dot{\boldsymbol{\varepsilon}}_{\boldsymbol{p}}\right)}$
Evolution of R with acc. plastic strain	$R(p) = \sigma_0 + Q_0 p + Q_\infty\left(1 - e^{-bp}\right)$

Sebastian Letz, 03.10.2018

Materials and methods

- General modeling strategy: Viscoplasticity computation

Viscoplastic strain by viscoplastic dissipation potential	$\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{vp}} = \left(\frac{\partial \Omega}{\partial \boldsymbol{\sigma}}\right)$
Combined inelastic treatment	$\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{in}} = \lambda \left(\frac{\partial f}{\partial \boldsymbol{\sigma}}\right) + \frac{\partial \Omega}{\partial \boldsymbol{\sigma}}$
Evolution of hardening variable	$\dot{r} = -\lambda \left(\frac{\partial f}{\partial R}\right) - \frac{\partial \Omega}{\partial R}$

Garofalo stationary creep law	$\dot{\varepsilon}_{vp} = C_1 [sinh(C_2 \sigma)]^{C_3} e^{-\frac{C_4}{T}}$
Combined creep (transient + stationary)	$\varepsilon_{vp} = \frac{C_1 \sigma^{C_2} t^{C_3+1}}{(C_3+1)} e^{-\frac{C_4}{T}} + C_5 \sigma^{C_6} t e^{-\frac{C_7}{T}}$
Perzyna viscoplasticity equation	$\dot{\varepsilon}_{vp} = \gamma \left[\left(\frac{\sigma}{\sigma_0}\right) - 1\right]^{\frac{1}{m}}$

Sebastian Letz, 03.10.2018

Materials and methods

- Model parameterization
  - Creep models: Extraction of secondary creep rates and stresses, linear fitting
  - Non-linear fitting (LM-algorithm) of primary creep
  - Perzyna model: Transformation into relaxation data → $\sigma = \sigma_0 \left[1 + \frac{\left(\varepsilon_{vp} t^{-1}\right)^m}{\gamma}\right]$
  - Global non-linear fitting of rearranged Perzyna model

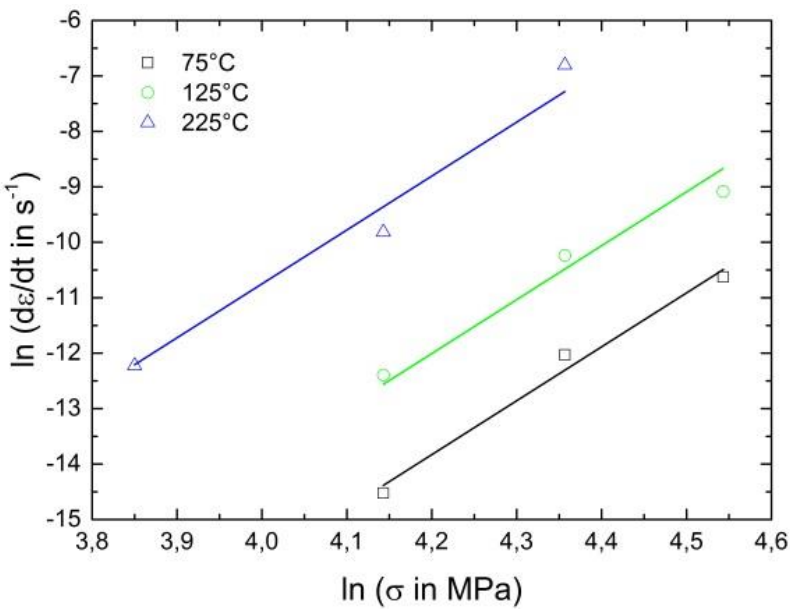

Fig.: Parameterization of Norton stationary creep law.

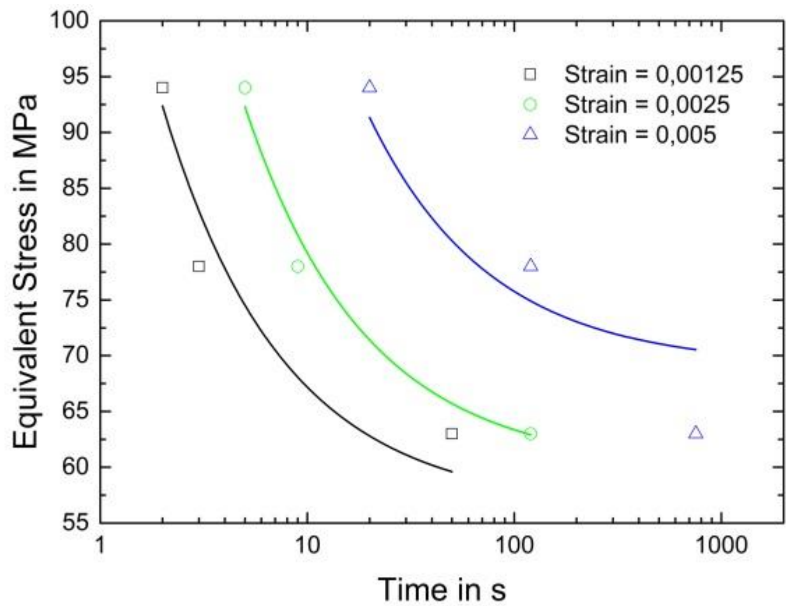

Fig.: Parameterization of Perzyna viscoplasticity by relaxation data..

Results and discussion

- Uniaxial creep loading experiments
  - Summary of all tests
  - Only primary and secondary creep
  - Missing elastic offset strain

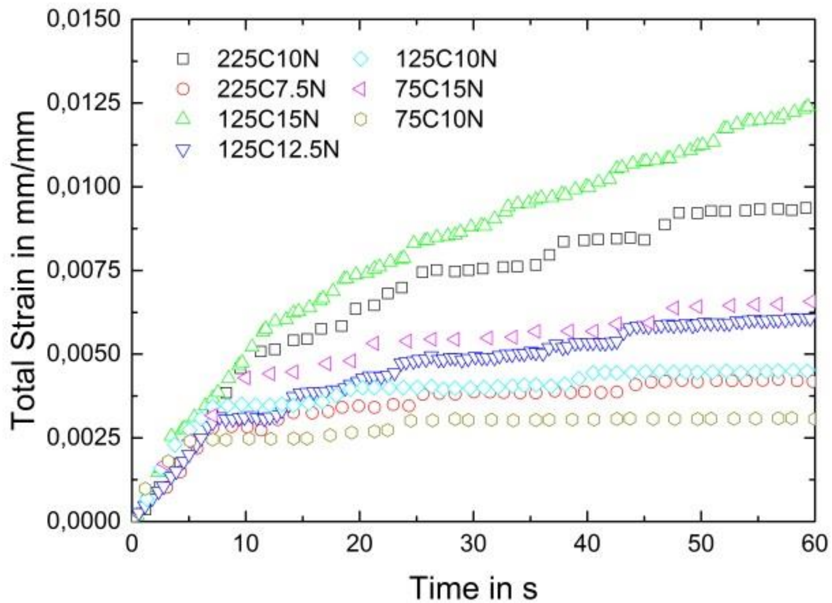

Fig.: Summary of uniaxial creep testing results.

- Hardening experiments and model predictions
  - Hardening deacreases with increasing temperature
  - At 225°C perfect plasticity
  - Good predicition at this strain rate in this strain regime

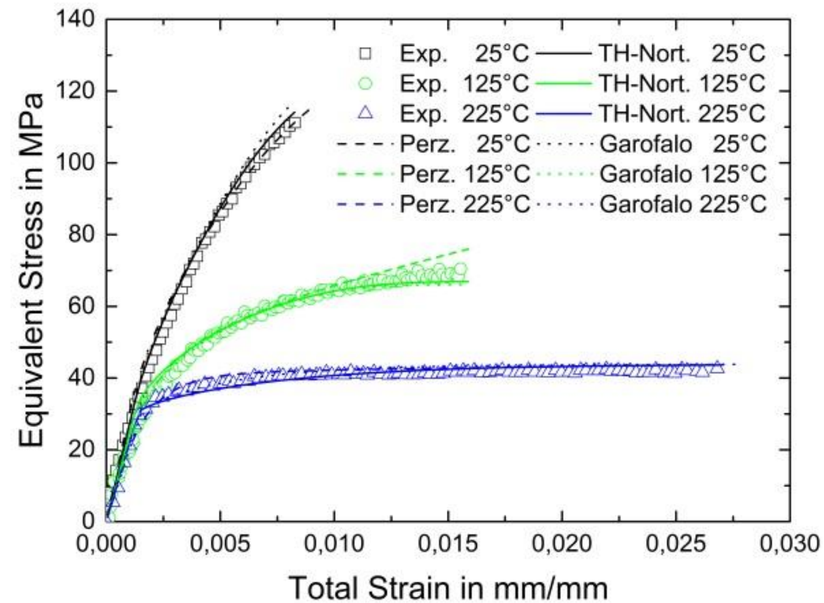

Fig.: Monotonic hardening experiment results and model predictions.

Sebastian Letz, 03.10.2018

Results and discussion

- Multiple-Hardening-Relaxation (MHR) computations: Results overview
  - Hardening: const. displacement rates: 1E-03 s^{-1}, 2E-03 s^{-1}, and 3E-03 s^{-1}
  - Hardening segments are followed by holding segments for 100 s
  - Creep models show the same trend during relaxation
  - Faster relaxation response for Perzyna model

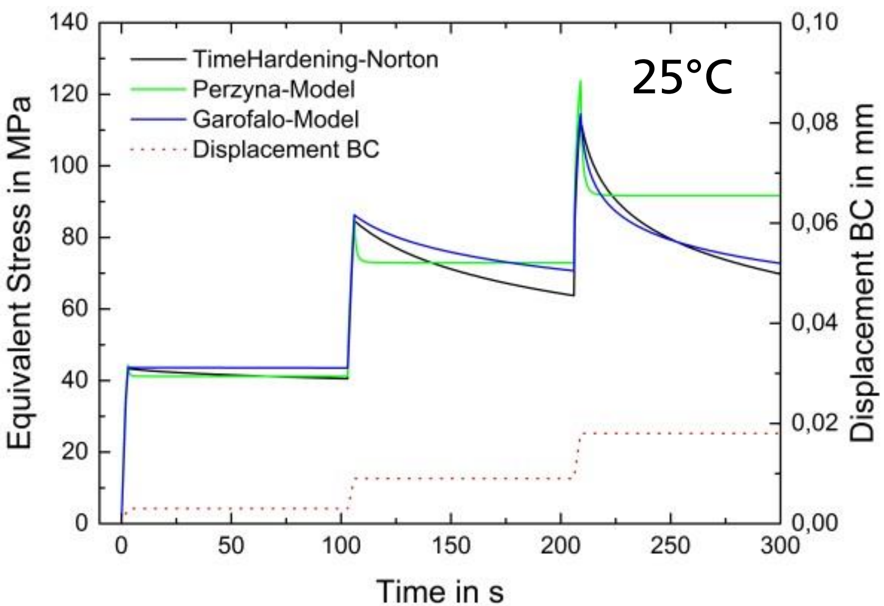

Fig.: Multiple-Hardening-Relaxation computations results at 25°C.

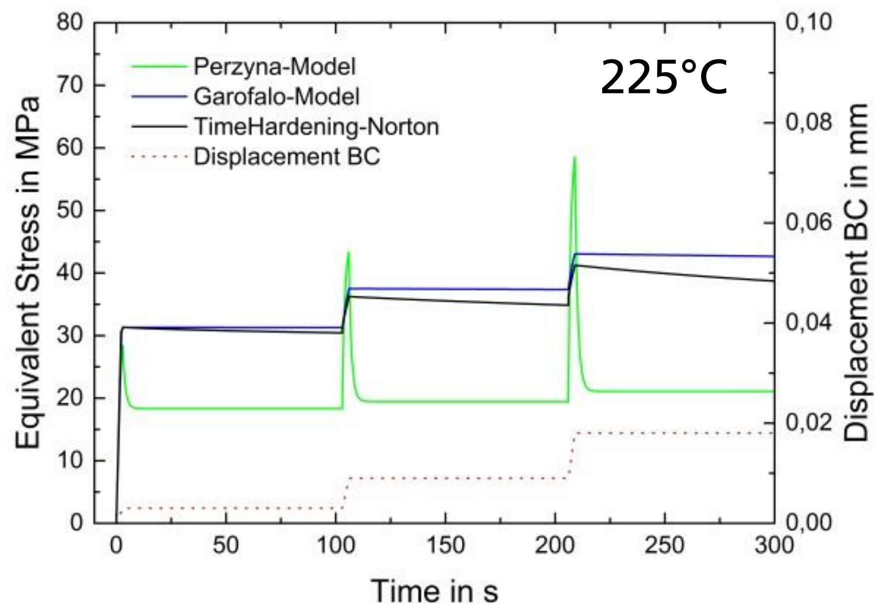

Fig.: Multiple-Hardening-Relaxation computations results at 225°C.

Sebastian Letz, 03.10.2018

ESREF 2018

Fraunhofer IISB

Results and discussion

- Multiple hardening computations: Transfomed Stress-Strain data
  - Unequal hardening characteristic of Perzyna and creep models
  - Only for higher strain rates and temperatures
  - Creep models converge to static plastic solution

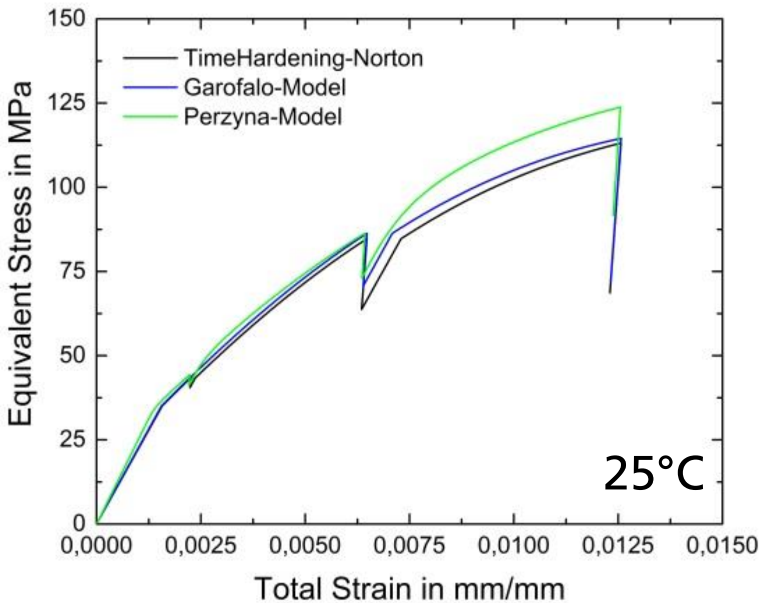

Fig.: Transformed stress-strain data of MHR computation at 25°C.

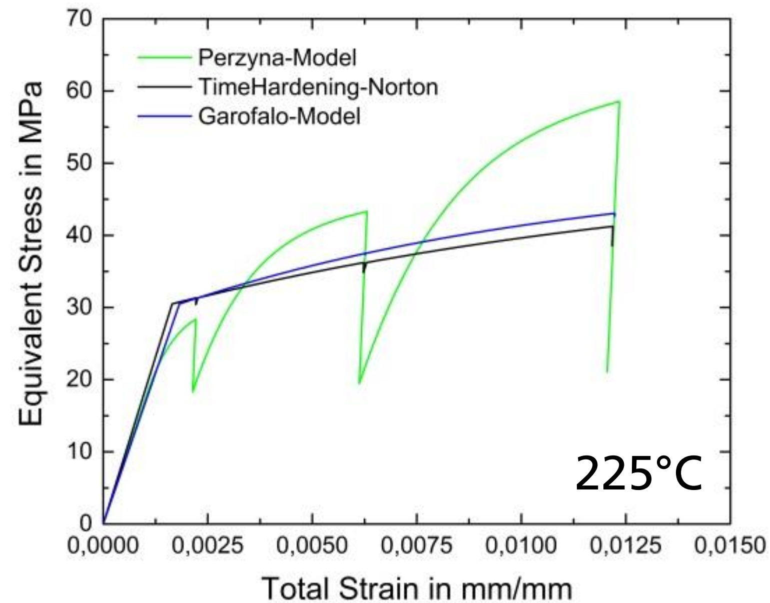

Fig.: Transformed stress-strain data of MHR computation at 25°C.

Sebastian Letz, 03.10.2018

Results and discussion

- Multiple hardening computations: The creep models
  - Stress dependency less pronounced at higher temperature
  - Relaxation is less pronounced at higher Temp., reversely expected!
  - Reason: Computation scheme for plastic and creep strains
  - Lower temp.: Plasticity law yields low strains for high stresses. Impact of viscous strain is high.
  - Higher temp.: Instantaneous plasticity yields high strains at relatively low stresses. Viscous strains are small and plasticity is predominant.

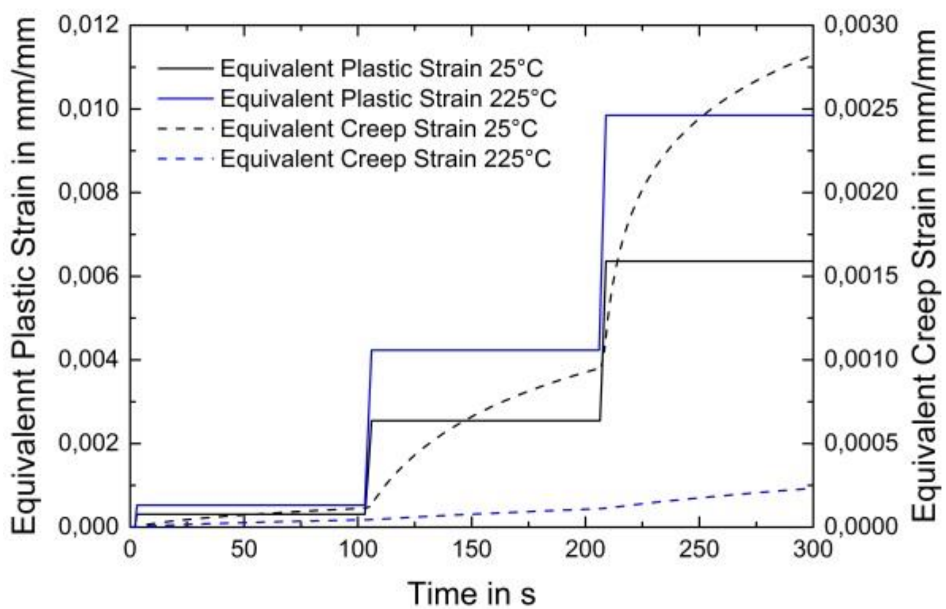

Fig.: Strain decomposition for Multiple-Hardening-Relaxation computations.

Results and discussion

- Multiple hardening computations: The Perzyna model
  - Different response compared to creep models
  - Tight database for the parameterization
  - Inelastic strain is obtained by a combined single viscoplastic potential

$$\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{in}} = \frac{\partial \Omega_{vp}}{\partial \boldsymbol{\sigma}}$$

  - Accumulated viscoplastic strain rate yields the inelastic strain rate

$$\dot{r} = -\frac{\partial \Omega_{vp}}{\partial R} = \gamma \left[\left(\frac{\sigma}{\sigma_0 + Q_0 r + Q_\infty \left(1 - e^{-br}\right)} \right) - 1 \right]^{\frac{1}{m}}$$

  - Hardening influences plastic strain rate, creep strain is calculated independently from the plastic strain
  - Multiplicative connection between plasticity and viscoplasticity could lead to a much stronger interaction compared to additive creep analysis

Sebastian Letz, 03.10.2018

Summary, conclusions and next steps

- Creep and monotonic hardening tests at different conditions were conducted on sintered silver films
- Three approaches to model the rate-dependency + instantaneous plastic strain were considered
- Different load scenarios were computed and compared
- The hardening experiments were correctly predicted by all models
- For multiple-hardening-relaxation computation, large differences between the Perzyna and the creep models were observed
- Multiplicative coupling of the viscous effect and the static plasticity yields a strong interaction and a higher sensitivity on the model parameters
- Next steps (ongoing):
  - Conduct MHR-Tests in different time and stress domains
  - Compare model predictions with experimental results and determine the domain of validity for each model for sintered silver layers

Thank you for your attention!

Sebastian Letz
sebastian.letz@iisb.fraunhofer.de
Fraunhofer-Institute for Integrated Systems and Device Technology
Schottkystraße 10 • 91058 Erlangen • Tel. 09131 / 761-619
www.iisb.fraunhofer.de