Department of Materials Science and Engineering

Flow Curve Measurement

Upset – Rastegaev method

Metal Forming (BMEGEMTAGE1) 2022/23-1

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***Flow stress** (σ_f) :*

The stress needed to start then maintain the plastic deformation in *uniaxial* state of stress.

$$\boxed{\sigma_f = f(\varphi_{eqv}, \dot{\varphi}_{eqv}, T)}$$

The flow stress of a given material, in given thermodynamic state, depends on the deformation and two state variables, the deformation rate and the forming temperature.
(The third state variable, the state of stress, is fixed).

Affect of temperature

Dependence on temperature

$$\boxed{k_f = f(\varphi_{eqv}, \dot{\varphi}_{eqv}, T)}$$

Cold forming ($T < T_{rekr}$)

$$\boxed{k_f \cong f(\varphi_{eqv})}$$

(generally at room temperature)

Hot forming ($T > T_{rekr}$)

$$\boxed{k_f \cong f(\dot{\varphi}_{eqv}, T)}$$

How to establish uniaxial state of stress?

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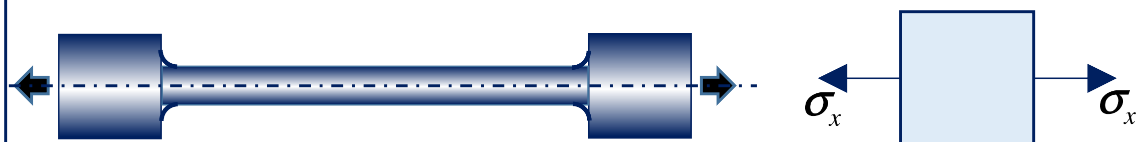
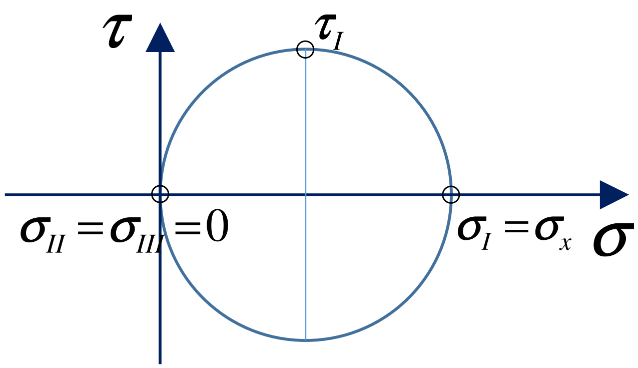
Uniaxial tension (up to the necking/contraction)





Uniaxial state of stress

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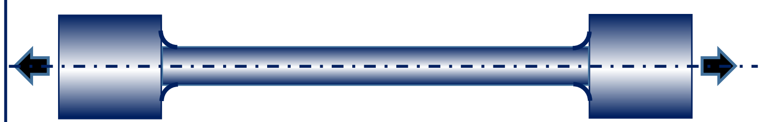
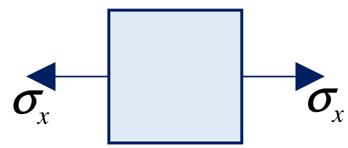
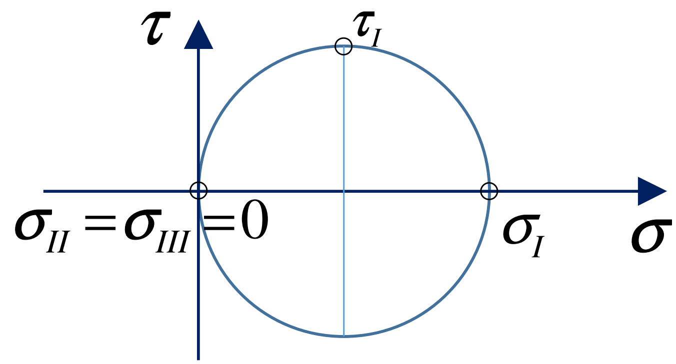
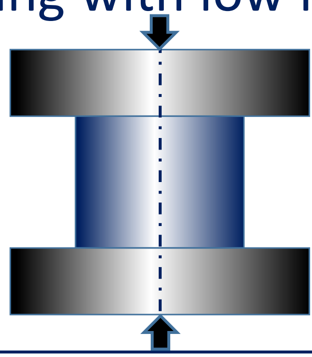
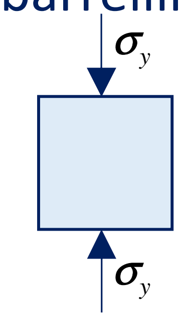


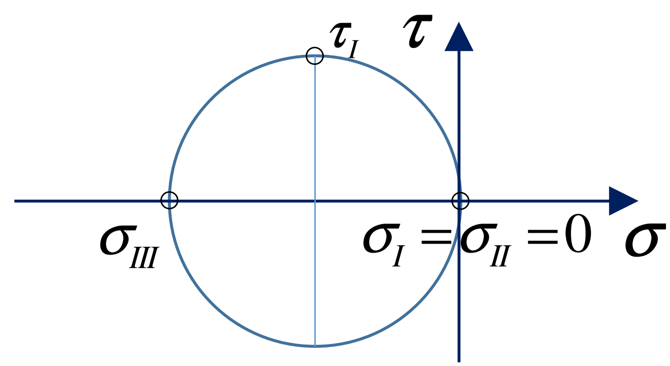




Upsetting with low friction (up to barrelling)







Flow stress measurements

The measurement of the flow stress is a complex task, as the uniaxial state of stress can't be maintained up to large deformations, and the specimen temperature and strain rate also can't be kept constant during the measurement.

The measurements might be grouped (overlapping is possible):

- The **flow stress is calculated** using a plastic theory (HMH), when multiaxial state of stress is existing in the specimen.
  Tensile test of cylindrical specimens at the contracted stage.
- The test is made in **approximately frictionless conditions.**
  Upsetting of cylindrical specimens (Rastegaev), furthermore, upsetting of flat specimens in plane strain condition (Watts-Ford), where the state of stress is not uniaxial.
- The measurement conditions are so defined, that those make possible to **conclude from the measured results to the data which are valid in uniaxial state of stress**.
  Extrapolation based on the upsetting of cylindrical specimens having different geometry (e.g. same diameter but different height).

Evaluation of the measurements

In uniaxial state of stress and in plane strain conditions the equations needed for the evaluations are simple. In both cases the principal coordinate system of stresses is applicable.

$$\sigma_{ij} = \begin{bmatrix} \sigma_I & 0 & 0 \\ 0 & \sigma_{II} & 0 \\ 0 & 0 & \sigma_{III} \end{bmatrix}, \qquad \varphi_{ij} = \begin{bmatrix} \varphi_I & 0 & 0 \\ 0 & \varphi_{II} & 0 \\ 0 & 0 & \varphi_{III} \end{bmatrix}$$

Principal stresses:

$$\sigma_I \geq \sigma_{II} \geq \sigma_{III}$$

Volume constancy:

$$\varphi_I + \varphi_{II} + \varphi_{III} = 0$$

Uniaxial tension: $\sigma_{II} = \sigma_{III} = 0,\quad \varphi_{II} = \varphi_{III} = -\varphi_I / 2$

Uniaxial compression: $\sigma_I = \sigma_{II} = 0,\quad \varphi_I = \varphi_{II} = -\varphi_{III} / 2$

Applying the HMH theory for the case of axial symmetry :

Equivalent stress $$\sigma_{eqv} = \sigma_I - \sigma_{III}$$

Flow criteria $$\sigma_{eqv} = \sigma_I - \sigma_{III} = \sigma_f$$

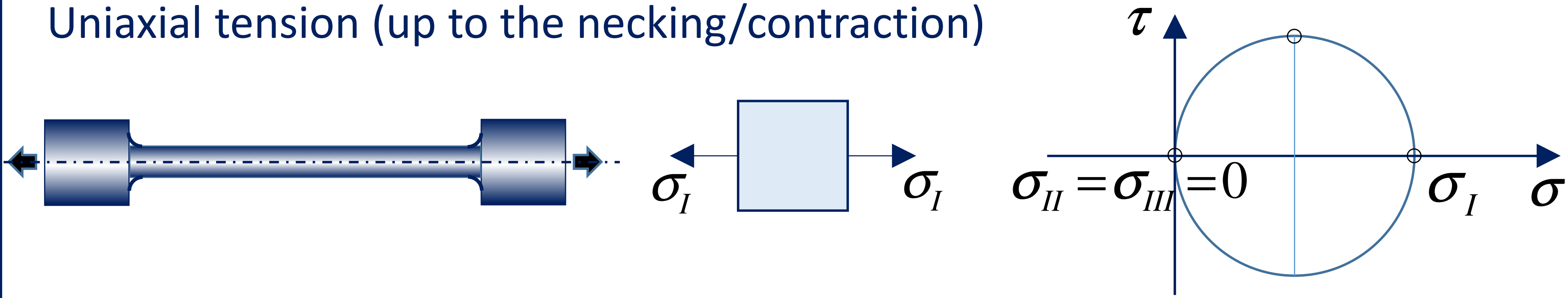
Flow criteria in uniaxial state of stress:

tension $\sigma_I = \sigma_f$ as $\sigma_{III} = 0$

compression $-\sigma_{III} = \sigma_f$ as $\sigma_I = 0$

Uniaxial state of stress

Uniaxial tension (up to the necking/contraction)

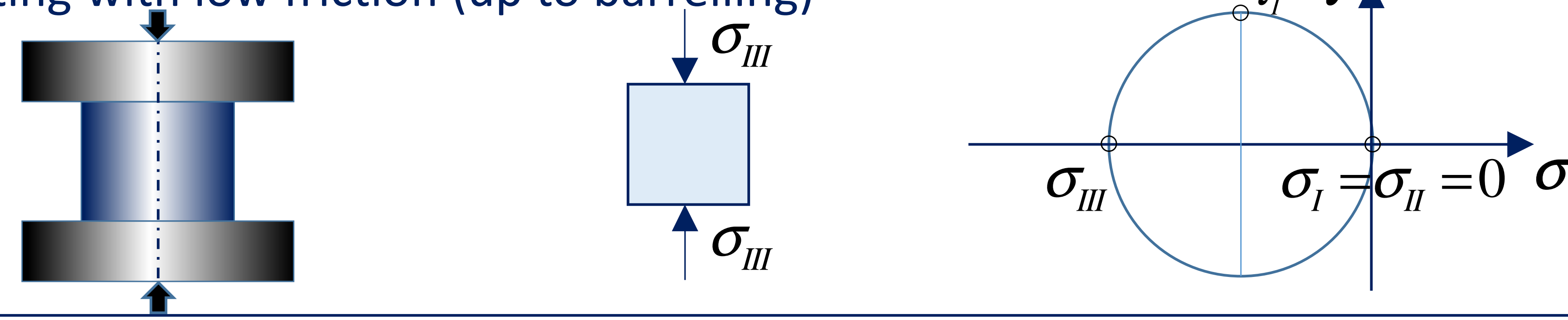


$$\sigma_I = \sigma_f = \frac{F}{A} = \frac{4F}{d^2 \pi}$$

$$\varphi_{eqv} = \varphi_I = \ln \frac{A_o}{A} = \ln \frac{d_o^{\,2}}{d^2} = 2 \ln \frac{d_o}{d}$$

Uniaxial state of stress

Upsetting with low friction (up to barrelling)



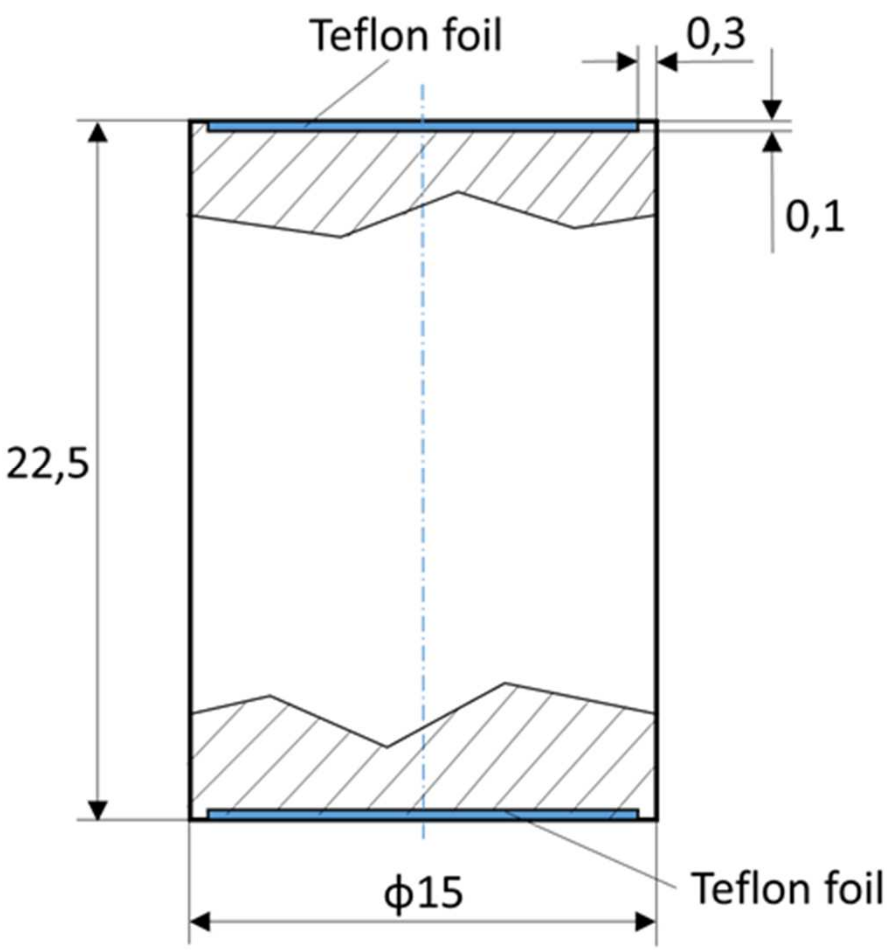
$$\boxed{-\sigma_{III} = \sigma_f = \frac{F}{A}}$$

where $A = \dfrac{A_o h_o}{h}$ as $V_o = A_o h_o = A h$

$$\boxed{\varphi_{eqv} = \varphi_{III} = \ln\frac{A}{A_o} = \ln\frac{h_o}{h}}$$

as $\dfrac{A}{A_o} = \dfrac{h_o}{h}$

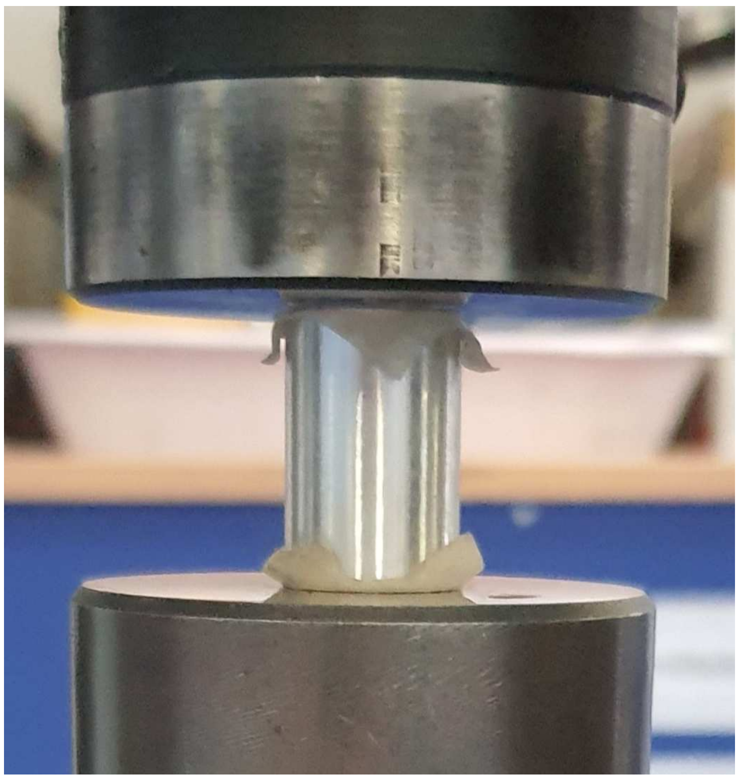
Rastegaev method – compression in uniaxial state of stress:

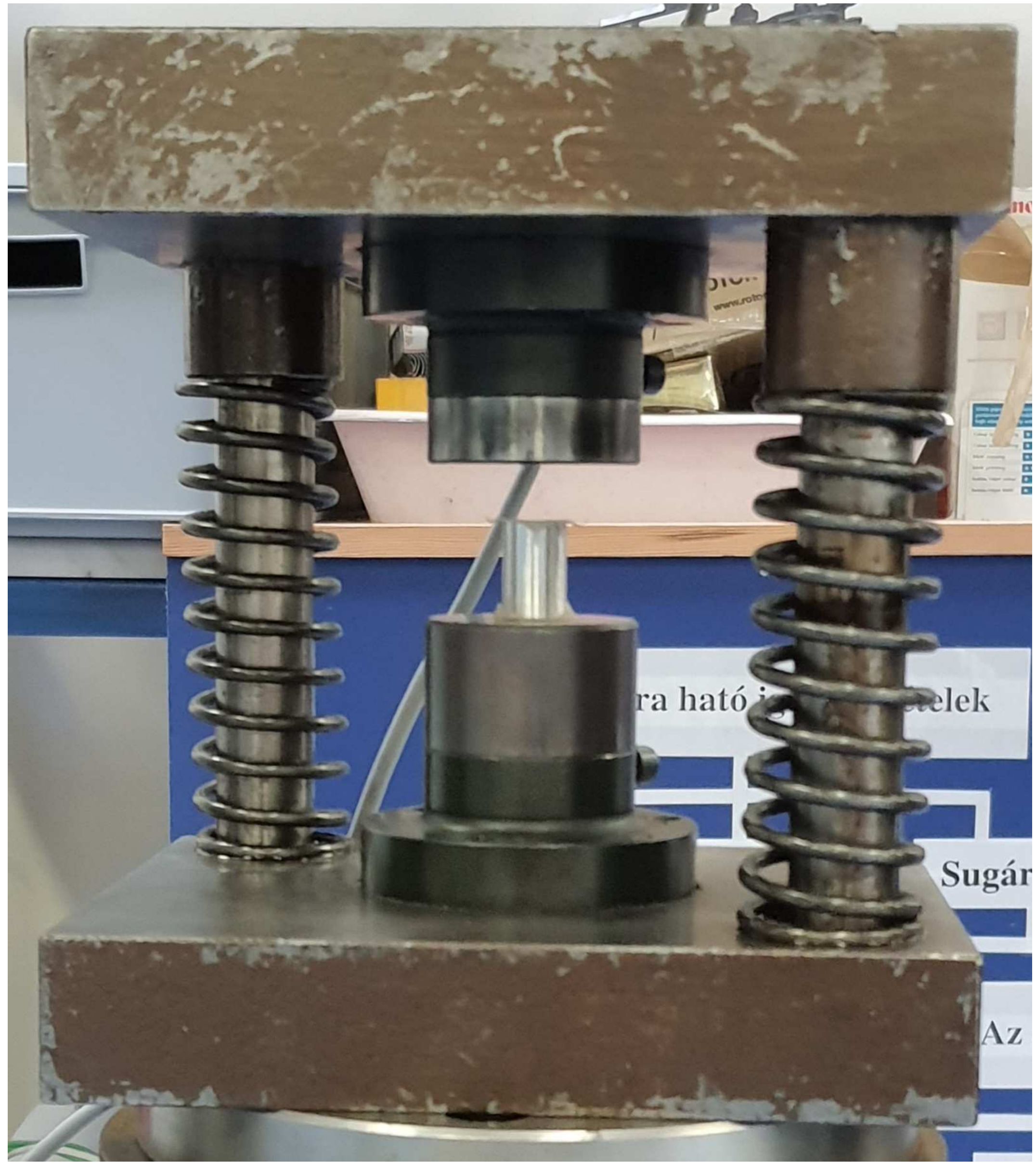


$$\sigma_f = \frac{F}{A} = \frac{F\,h}{A_o\,h_o}$$

$$\varphi_{eqv} = \ln\frac{A}{A_o} = \ln\frac{h_o}{h}$$

Mérés





Mérés


TIRA test 2300
FŐKAPCSOLÓ
Sugárfizikai
Biológiai
Korrózió
Általános
Elektrokémiai
Rés, lyuk
Hidrogén elridegedés


ORIGIN
Mitutoyo
ON/OFF
ZERO/ABS
ABSOLUTE
DIGIMATIC

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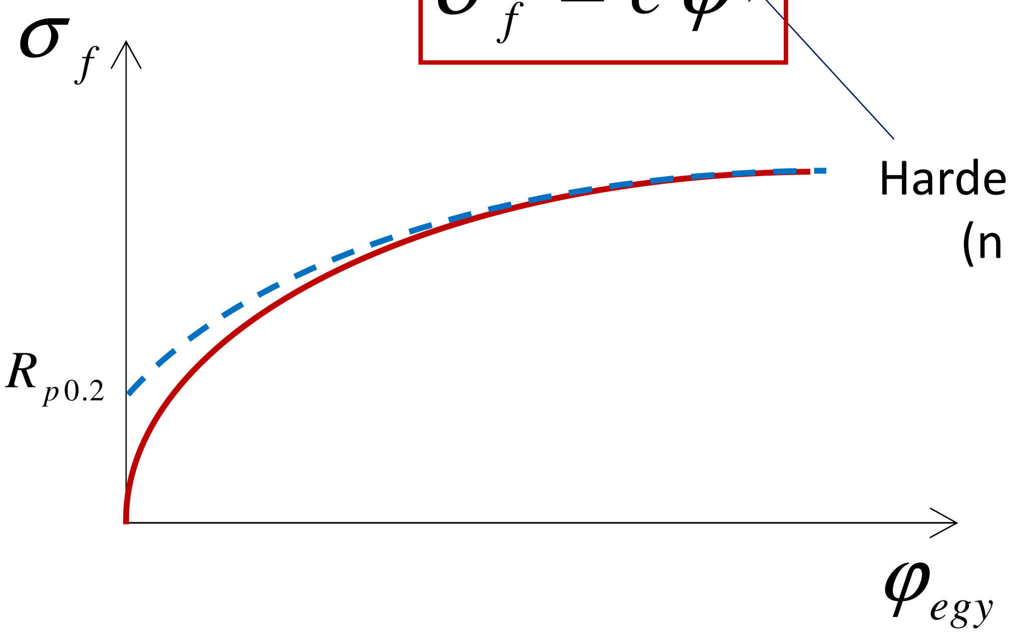
Constitutive equations

Approximate empirical functions can be fitted on the measurement points :

$$\boxed{\sigma_f = c\,\varphi^n}$$

$$\sigma_f = \sigma_{f0} + c'\varphi^{n'}$$



Hardening coefficient
(n = 0.1 – 0.3)

$$\sigma_{fo} = R_{p0,2}$$

For small deformations the $\boldsymbol{\sigma_f = c\,\varphi^n}$ formula gives not good approximation (1-2%), as the curve starts from zero. But, for bigger deformations it gives good approximation for calculation of the flow stress.

The $\boldsymbol{\sigma_f = c\,\varphi^n}$ formula is from Sándor Nádai (Alexander Nadai), but before, Sándor Rejtő used first for shearing stresses. (His statue is in the department lobby.)

Thank you for your attention!