TALAT
Training in Aluminium Application Technologies

TALAT Lecture 3300

Fundamentals of Metal Forming

18 pages, 27 figures

Basic Level

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Objectives:

– a brief review of the fundamental terms and laws governing metal forming at room temperature as well as at high temperatures. This lecture is a necessary prerequisite to understand the more specific treatment of metal forming subjects such as forging, impact extrusion and sheet metal forming in the subsequent TALAT Lectures 3400 to 3800.

Prerequisites:

– General background in production engineering, machine tools

Date of Issue: 1996

3300 Fundamentals of Metal Forming

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3301 Introduction

3301.01 Definition of Forming

The general description given in **Figure 3301.01.01** defines metal forming by plastic deformation and distinguishes it from other forming and shaping processes like casting and machining.

Definition of Forming

Forming is a fabrication process for solid substances by controlled plastic deformation in order to obtain alterations of:

- the form,
- the material properties and/or
- the surface properties,

whereby the mass and material continuum remain unchanged.

K.Siegert

TALAT Training in Aluminium Application Technologies	Definition of Forming	3301.01.01

3302 Terms for Classifying Forming Processes

- Classification by State of Stress
- Classification by Type of Raw Material
- Classification by Forming Temperature
- Classification by Methods of Induction of Forces into the Work-Piece

3302.01 Classification by State of Stress (Figure 3302.01.01)

Terms for classifying the forming process:
Classification by State of Stress

Pressure Forming	DIN 8583	Rolling, Open-Die Forming, Die Forming, Indenting, Pressing Through
Tension-Compression Forming	DIN 8584	Drawing, Deep Drawing, Collar Forming, Compressing, Upset Bulging
Tension Forming	DIN 8585	Stretch Reducing, Bulge Forming, Stretch Forming
Bend Forming	DIN 8586	Bending with Linear Tool Movement, Bending with Rotating Tool Movement
Shear Forming	DIN 8587	Shear Displacement, Twisting

TALAT Training in Aluminium Application Technologies | Classifying the Forming Process by State of Stress | 3302.01.01

3302.02 Classification by Type of Raw Material (Figure 3302.02.01)

Terms for classifying the forming process:
Type of Raw Material

Sheet Forming

The raw material consists of flat parts of constant thickness.

The parts produced have a three-dimensional form with approximately constant wall thickness (≈ raw material thickness).

Bulk Forming

Raw parts are three-dimensional.

The parts produced are also three-dimensional but often have very different wall thicknesses and/ or cross-sections.

TALAT Training in Aluminium Application Technologies | Classifying the Forming Process by Types of Raw Materials | 3302.02.01

3302.03 Classification by Forming Temperature (Figure 3302.03.01)

Terms for classifying the forming process:
Forming Temperature

Cold Forming

Process in which the work-piece is not heated before forming, but instead formed at room temperature.

$\vartheta = \vartheta_{Room}$ (ca. 20° C)

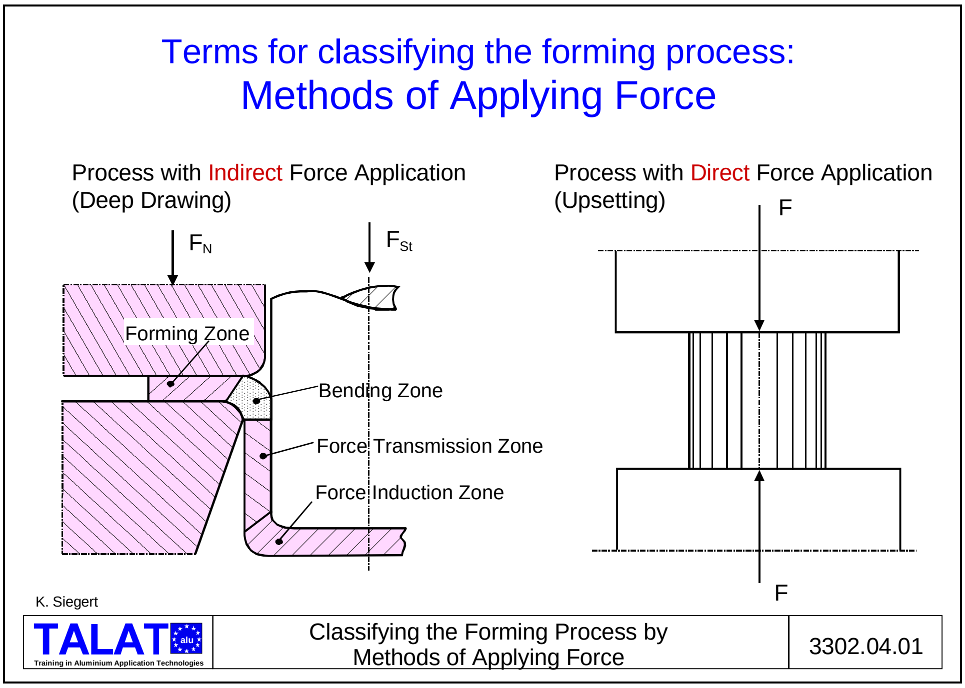
Warm Forming

Process in which the work-piece is heated to an elevated temperature higher than room temperature before forming.

$\vartheta > \vartheta_{Room}$ (ca. 20° C)

TALAT	Classifying the Forming Process by Forming Temperature	3302.03.01

3302.04 Classification by Methods of Induction of Forces into the Work-Piece (Figure 3302.04.01)



3303 Characteristic Values and Basic Laws of Metal Forming

- Flow Stress
- Plastic Strain, Rate and Acceleration
- Plastic Flow under Combined Stresses
- Law of Plastic Flow
- Flow Curves
- Average Flow Stress
- Energy Considerations

3303.01 Flow Stress

(Figure 3303.01.01)

Characteristic Values, Basic Laws

Flow Stress

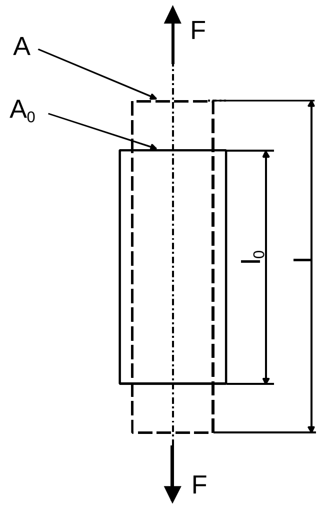
The flow stress (resistance to plastic deformation) of a material is the stress required to initiate or continue plastic deformation under uniaxial state of stress.

Flow stress (true stress) $k_f = \frac{F}{A}$

By comparison (technical stress) $\sigma = \frac{F}{A_0}$

Conversion: with $\varepsilon = (l - l_0) / l_0$

one obtains $k_f = \sigma(\varepsilon_l + 1)$

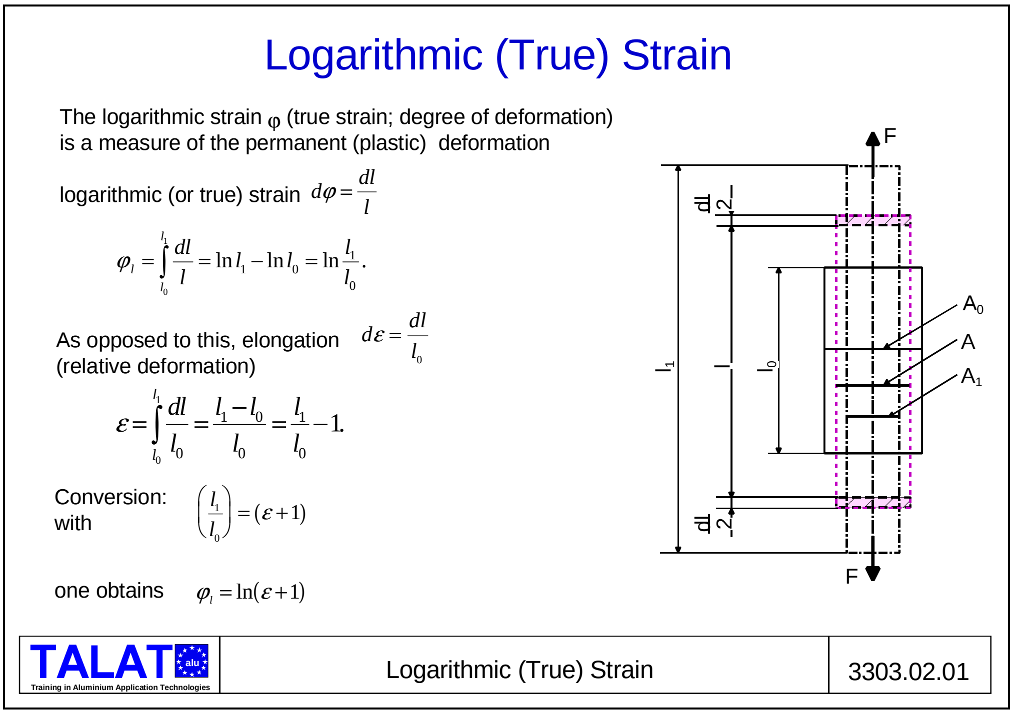


TALAT Training in Aluminium Application Technologies	Definition of Flow Stress	3303.01.01

3303.02 Plastic Strain, Rate and Acceleration

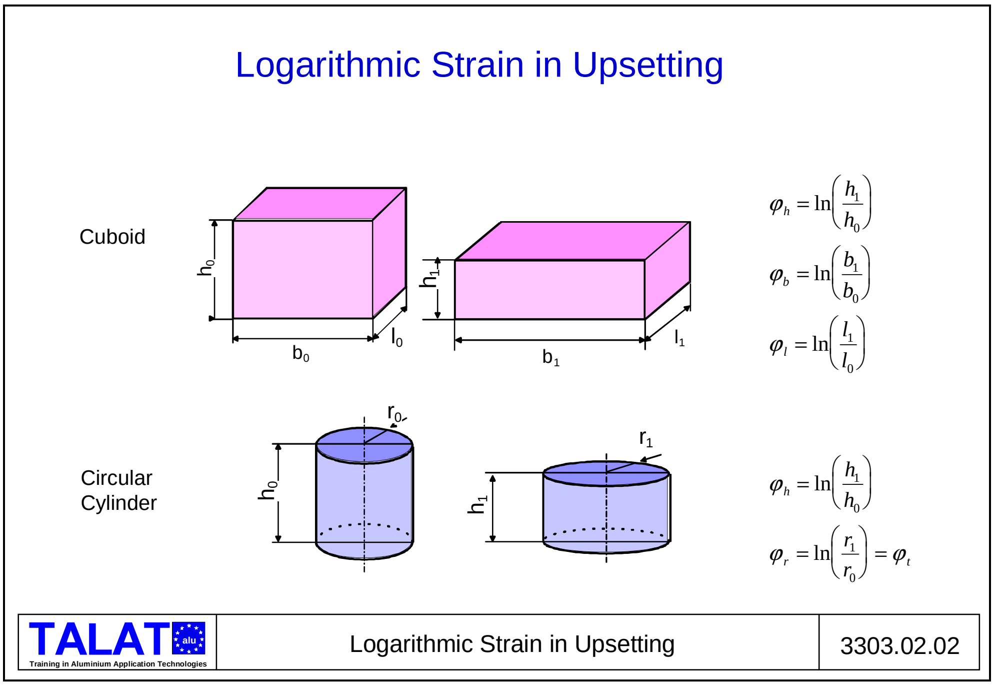
Logarithmic (True) Plastic Strain

(Figure 3303.02.01)



Logarithmic Strain in Upsetting

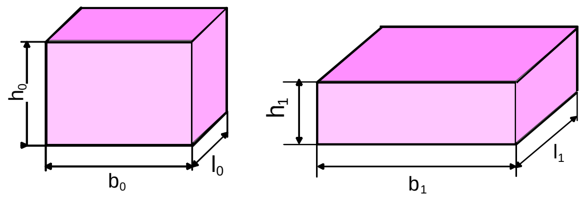
(Figure 3303.02.02)



Law of Volume Constancy

(Figure 3303.02.03)

Law of Volume Constancy



Assuming that during forming the volume of a cuboid remains constant, the following equation is valid for a homogeneous compression:

$$V = h_1 \cdot b_1 \cdot l_1 = h_0 \cdot b_0 \cdot l_0$$

so that:

$$\left(\frac{h_1}{h_0}\right) \cdot \left(\frac{b_1}{b_0}\right) \cdot \left(\frac{l_1}{l_0}\right) = 1$$

Taking the logarithms of both sides:

$$\ln\left(\frac{h_1}{h_0}\right) + \ln\left(\frac{b_1}{b_0}\right) + \ln\left(\frac{l_1}{l_0}\right) = 0$$

or:

$$\varphi_h + \varphi_h + \varphi_h = 0 \quad \text{or} \quad \sum \varphi = 0$$

TALAT Training in Aluminium Application Technologies	Law of Volume Constancy	3303.02.03

Plastic Strain Rate

(Figure 3303.02.04)

Plastic Strain Rate

(True strain rate)

The true strain rate or logarithmic strain rate $\dot{\varphi}$ is the derivative of the logarithmic strain (true strain) φ with time *t*:

$$\dot{\varphi} = \frac{d\varphi}{dt}$$

From the law of volume constancy one obtains:

$$\dot{\varphi}_h + \dot{\varphi}_b + \dot{\varphi}_l = 0$$

$$\sum \dot{\varphi} = 0$$

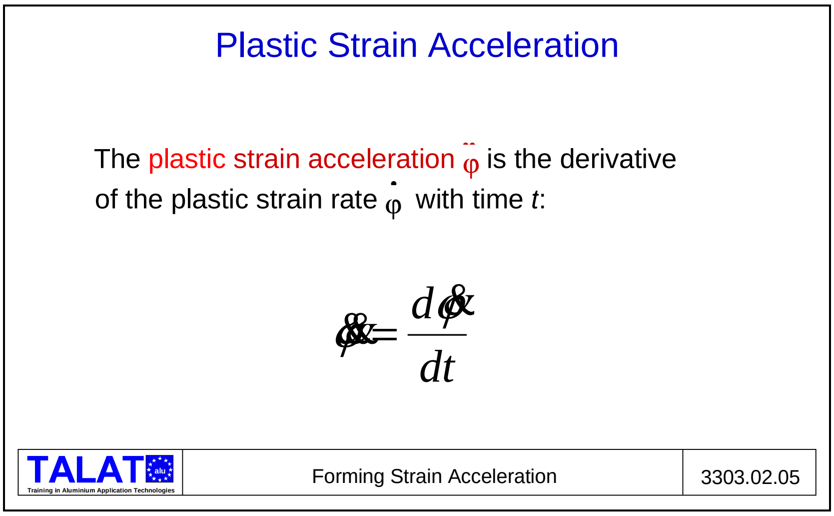
One has to differentiate between the strain rate $\dot{\varphi}$ and the tool speed v_{wz}. For a homogeneous compression where h = instantaneous height of the material being compressed, the following relation is valid:

$$\dot{\varphi} = \frac{v_{wz}}{h}$$

TALAT Training in Aluminium Application Technologies	Plastic Strain Rate (True Strain Rate)	3303.02.04

Plastic Strain Acceleration

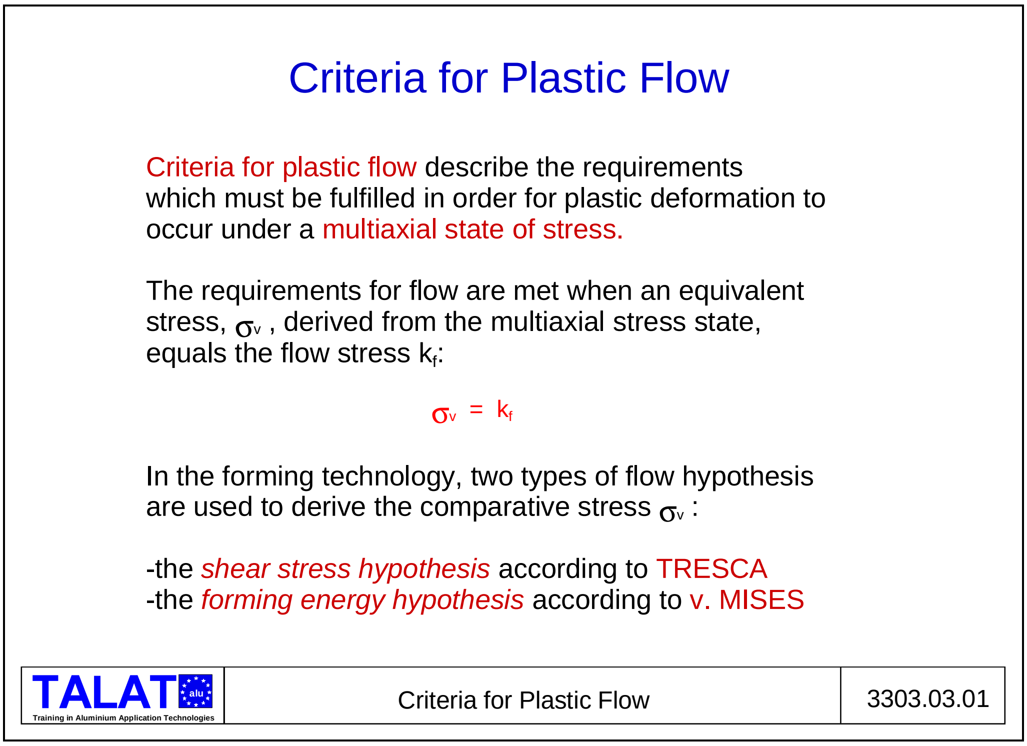
(Figure 3303.02.05)



3303.03 Plastic Flow under Combined Stresses

Criteria for Plastic Flow

(Figure 3303.03.01)



Maximum Shear Stress Hypothesis

(Figure 3303.03.02, Figure 3303.03.03, Figure 3303.03.04)

Shear Stress Hypothesis (1)

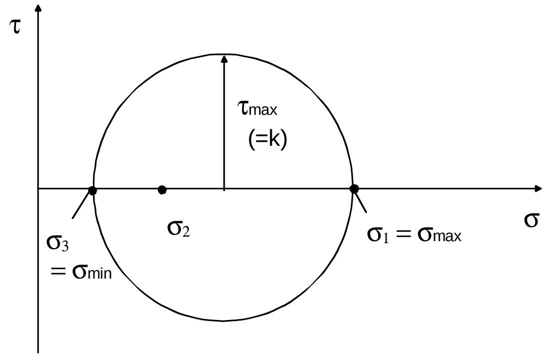
Flow occurs when the maximum shear stress τ_{max} reaches a value characteristic for the material, the so-called shear yield stress k:

$$\tau_{max} = k\ .$$

Based on the stresses ($\sigma_1 > \sigma_2 > \sigma_3$) in the MOHR stress circle, the following equations can be derived:

$$\tau_{max} = \frac{1}{2}\ (\sigma_1 - \sigma_3) = k$$

$$\tau_{max} = \frac{1}{2}\ (\sigma_{max} - \sigma_{min}) = k$$



TALAT Training in Aluminium Application Technologies | Shear Stress Hypothesis (1) | 3303.03.02

Shear Stress Hypothesis (2)

For a uniaxial state of tensile stress ($\sigma_1 = \sigma_{max}$, $\sigma_2 = \sigma_3 = \sigma_{min} = 0$), the following relationship is valid:

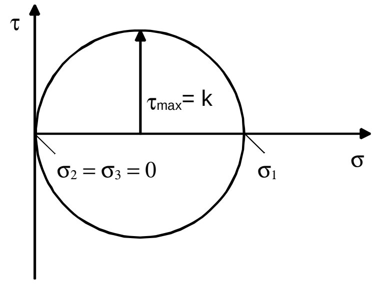
$\sigma_{max} - \sigma_{min} = \sigma_1 = 2k$

and (definition of flow stress)

$\sigma_1 = k_f$.

Considering the flow conditions ($\sigma_v = k_f$), one obtains:

$\sigma_v = k_f = \sigma_{max} - \sigma_{min}$.



Thus, flow starts when the difference between the largest and smallest principal normal stresses equals the flow stress.

TALAT Training in Aluminium Application Technologies | Shear Stress Hypothesis (2) | 3303.03.03

Shear Stress Hypothesis (3)

According to the shear stress theory, the comparative deformation strain is equal to the largest value of the logarithmic deformation strain:

$$\varphi_g = \left(|\varphi_1|, |\varphi_2|, |\varphi_3|\right)_{\max}.$$

φ_g is the principal logarithmic (or true) strain.

TALAT Training in Aluminium Application Technologies	Shear Stress Hypothesis (3)	3303.03.04

Mises Flow Criterion

(Figure 3303.03.05)

Distortion Energy (von-Mises) Theory

Flow sets in when the elastic distortion energy for changing the form exceeds a criterical value.

If $\sigma_1 > \sigma_2 > \sigma_3$, then the comparative stress is given by

$$\sigma_v = k_f = \sqrt{\frac{1}{2}\left\langle(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right\rangle}.$$

Using the average stress

$$\sigma_m = \frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)$$

one obtains

$$\sigma_v = k_f = \sqrt{\frac{3}{2}\left\langle(\sigma_1-\sigma_m)^2+(\sigma_2-\sigma_m)^2+(\sigma_3-\sigma_m)^2\right\rangle}.$$

Then, according to the distortion energy theory, the comparative deformation strain becomes

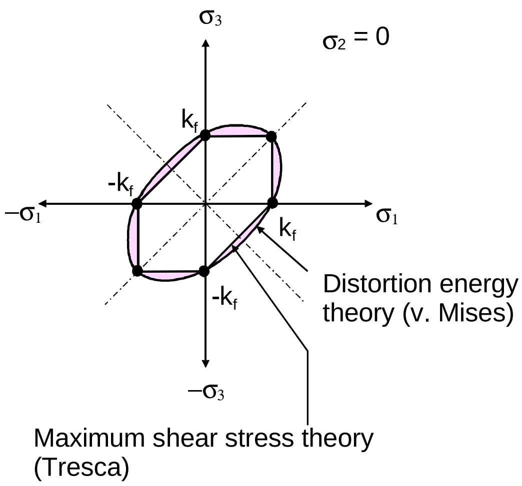
$$\varphi_v = \sqrt{\frac{2}{3}(\varphi_1^2+\varphi_2^2+\varphi_3^2)}.$$

TALAT Training in Aluminium Application Technologies	Distortion Energy Hypothesis (v. Mises)	3303.03.05

Yield Criteria for Plane Stress (Yield Locus)

(Figure 3303.03.06)

Yield Criteria for Plane Stress



The comparision of yield criteria for a plane state of stresses ($\sigma_2 = 0$) indicates the stress combinations σ_1 , σ_3 at which flow sets in.

The curves depicting the yield criteria can thus be considered as an illustration of the flow theory in the σ_1 , σ_3 plane state of stresses.

The two flow theories sometimes deliver somewhat different stress values for the start of flow. This difference is, however, small and does not exceed 15%.

TALAT Training in Aluminium Application Technologies	Yield Criteria for Plane Stress	3303.03.06

3303.04 Law of Plastic Flow

(Figure 3303.04.01)

Law of Plastic Flow

The law of plastic flow describes the correlation between stress and the resulting deformation strain for the plastic state.

Assuming that the ratios of the deformation strains among each other remain constant during the process, the correlation between the deformation strain φ and the principal stress σ which causes the deformation can be given by:

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$

$$\varphi_1 : \varphi_2 : \varphi_3 = (\sigma_1 - \sigma_m) : (\sigma_2 - \sigma_m) : (\sigma_3 - \sigma_m)$$

Important consequences:
The logarithmic deformation strain attains the value zero when the corresponding principal stress equals σ_m.

TALAT Training in Aluminium Application Technologies	Law of Plastic Flow	3303.04.01

3303.05 Flow Curves

General Definition of the Flow Curve

(Figure 3303.05.01)

Flow Curve

The flow stress k_f of a material depends on

- the logarithmic principal deformation strain φ_g
- the logarithmic principal deformation strain rate $\dot{\varphi}_g$
- the temperature ϑ

and, during the high speed forming, also on

- the principal deformation strain acceleration $\ddot{\varphi}_g$

i.e. $k_f = f(\varphi_g, \dot{\varphi}_g, \vartheta, (\ddot{\varphi}_g))$.

The flow curve is the illustration of the flow stress k_f as a function of φ_g, $\dot{\varphi}_g$, ϑ and $\ddot{\varphi}_g$.

TALAT Training in Aluminium Application Technologies	Flow Curve	3303.05.01

Flow Curves at Room Temperature

(Figure 3303.05.02, Figure 3303.05.03)

Flow Curves at Room Temperature (1)

In the range of cold forming (forming temperature ϑ is considerably lower than the recrystallisation temperature ϑ_{Rekr}), the flow stress k_f for most metallic materials depends only on the logarithmic principal deformation strain φ_g:

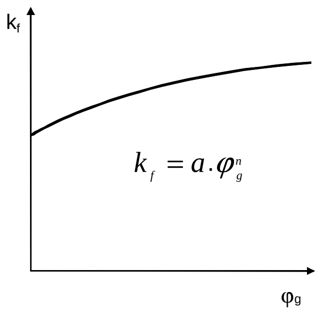
$$k_f = f(\varphi_g)$$

This dependence can be replaced for a number of materials by the approximate relationship

$$k_f = a.\varphi_g^n$$

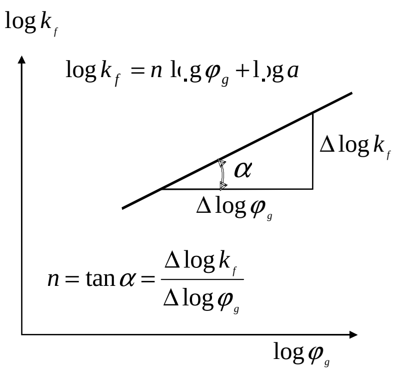
(valid for $\varphi_g \neq 0$, i.e. for $k_f \geq R_{p0.2}$ respectively approximation for $k_f \geq R_{eH}$)

(*a* and *n* are material constants; *n* is called *strain hardening exponent*)



TALAT Training in Aluminium Application Technologies	Flow Curves at Room Temperature (1)	3303.05.02

Flow Curves at Room Temperature (2)



By taking the logarithm of the equation $k_f = a\,\varphi_g^n$

$$\log k_f = n \log \varphi_g + \log a$$

The illustration of a flow curve of the form $k_f = a\,\varphi_g^n$ in a coordinate system with axes in a logarithmic scale is a straight line whose gradient is the coefficient n.

The coefficient n is a measure of the amount by which a material hardens with increasing deformation strain φ_g and is therefore known as the strain hardening coefficient.

Typical values of n for an aluminium-killed steel are in the range of

$$0.2 \leq n \leq 0.25$$

and for aluminium sheet alloys (AlMg0,4Si1,2 ka, AlMg,5Mn w) in the range of

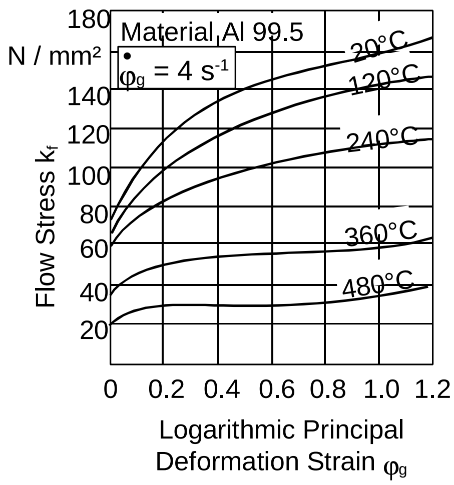
$$0.2 \leq n \leq 0.3$$

TALAT Training in Aluminium Application Technologies | Flow Curves at Room Temperature (2) | 3303.05.03

Flow Curves at Elevated Temperatures

(Figure 3303.05.04, Figure 3303.05.05 and Figure 3303.05.06)

Flow Curves at Elevated Temperature (1)



During forming at elevated temperatures (warm forming), the flow stress k_f depends on the logarithmic principal deformation strain φ_g, the forming temperature ϑ and the logarithmic principal deformation strain rate (deformation strain rate) $\dot{\varphi}_g$:

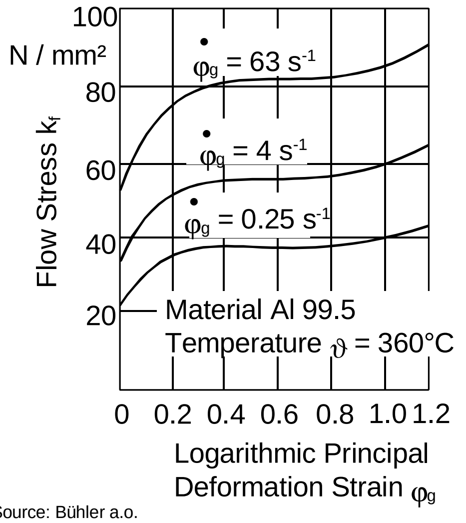
$$k_f = f(\varphi_g , \vartheta , \dot{\varphi}_g)$$

As a rule, the flow stress k_f decreases with increasing temperature ϑ for a given logarithmic principal deformation strain φ_g,

Source: Bühler a.o

TALAT Training in Aluminium Application Technologies | Flow Curves at Elevated Temperature (1) | 3303.05.04

Flow Curves at Elevated Temperature (2)

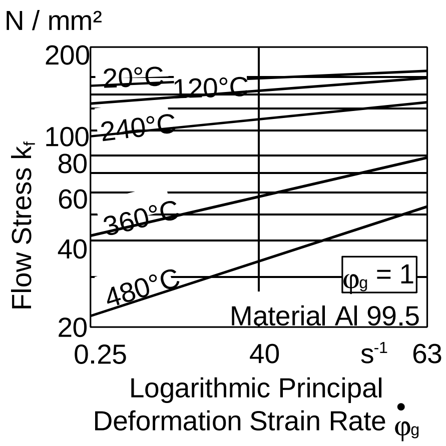


- With increasing temperature ϑ, the influence of the logarithmic principal deformation strain φ_g on the flow stress k_f decreases.
- The influence of the deformation strain rate $\dot{\varphi}_g$ on the flow stress k_f increases with increasing temperature ϑ. For a given logarithmic principal deformation strain φ_g and a given forming temperature ϑ, the flow stress k_f increases with increasing deformation strain rate $\dot{\varphi}_g$.

Source: Bühler a.o.

TALAT Training in Aluminium Application Technologies	Flow Curves at Elevated Temperature (2)	3303.05.05

Flow Curves at Elevated Temperature (3)



For a given logarithmic principal deformation strain φ_g and a given forming temperature ϑ, the relationship between the flow stress k_f and the deformation strain rate $\dot{\varphi}_g$ is given approximately by the equation

$$k_f = b \cdot \dot{\varphi}_g^m$$

The exponent *m* is a measure of the hardening of the material which depends on the deformation strain rate.
It increases with increasing temperature.

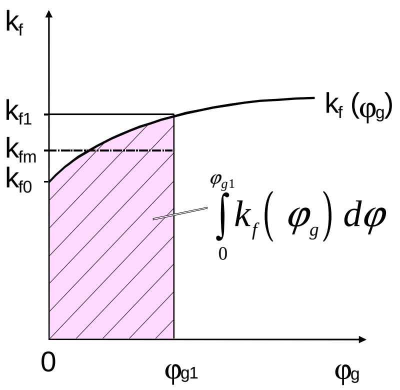
Source: Bühler a.o

TALAT Training in Aluminium Application Technologies	Flow Curves at Elevated Temperature (3)	3303.05.06

3303.06 Average Flow Stress

(Figure 3303.06.01)

Average Flow Stress



The calculation of stresses, energies and forces is simplified, if one uses an equivalent constant flow stress instead of the actual flow stress k_{fm}. For a forming process in the range $0 \leq \varphi_g \leq \varphi_{g1}$, it is defined as

$$k_{fm} = \frac{1}{\varphi_{g1}} \int_0^{\varphi_{g1}} k_f(\varphi_g)\, d\varphi$$

As an approximation, one can use

$$k_{fm} = \frac{k_{f0} + k_{f1}}{2}$$

k_{f0} - flow stress at start of process ($\varphi_g = 0$)
k_{f1} - flow stress at end of process ($\varphi_g = \varphi_{g1}$)

TALAT Training in Aluminium Application Technologies	Average Flow Stress	3303.06.01

3303.07 Energy Considerations

Forming Energy

(Figure 3303.07.01)

Forming Energy

Ideal forming energy

The ideal forming energy W_{id} is that part of mechanical energy which has to be used for the forming process without external friction and internal displacements.

The following relation is valid for the forming energy W_{id}:

$$W_{id} = V \int k_f(\varphi_g)\, d\varphi$$

where V is the formed volume.

Using the average flow stress k_{fm}, one obtains

$$W_{id} = V\, k_{fm}\, \varphi_g$$

Total energy (effective forming energy)

The total forming energy W_{ges} includes the ideal forming energy W_{id} as well as the energy required to overcome the external friction (W_R) and the internal displacement (W_{Sch}), so that

$$W_{ges} = W_{id} + W_R + W_{Sch}$$

TALAT Training in Aluminium Application Technologies	Forming Energy	3303.07.01

Heat Development during Forming

(Figure 3303.07.02)

Heat Developed during Forming

Forming processes are irreversible processes. The major part of the energy applied for the forming process is converted into heat, causing the work-piece to warm up. Assuming that the total forming energy W_{ges} is converted into heat and that no heat is lost to the environment (tool), the rise in temperature is given by the equation

$$\Delta \vartheta = \frac{W_{ges}}{V * \rho * c_p}$$

(V formed volume, ρ density and c_p specific heat of the work-piece material)

TALAT alu Training in Aluminium Application Technologies	Heat Developed during Forming	3303.07.02

Literature/References

K. Lange (Editor): Umformtechnik, Springer-Verlag, Berlin, Heidelberg, New York, Tokyo, 1984

List of Figures