Failure analysis in sheet metal forming - Introduction to the Forming Limit Curve (FLC)

testXpo presentation 2023

23.10.2023 Ulm / Dr. Harald Schmid

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1. Current challenges in sheet metal forming
2. Introduction to the forming limit curve
3. Test setup and analysis of the forming limit curve
4. Sheet Metal Testing Machines BUP
5. Summary and outlook

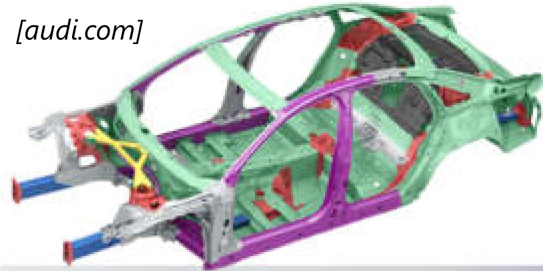
Current challenges in sheet metal forming

The demand for CO2 reduction and low vehicle weight requires consistent lightweight design.

Forecast of the global sheet metal market until 2027

In sheet metal forming, lightweight design leads...

- to more complex component geometries
- to multi-material design ("the right material in the right place")
- to the adaptation and change of methods and processes
- to further growth of the sheet metal market worldwide
- to the replacement of conventional materials with modern lightweight materials



Body in multi-material construction and front door

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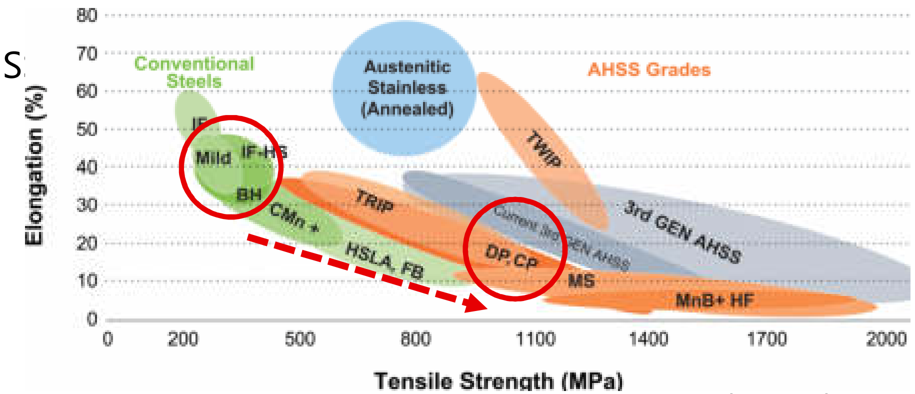
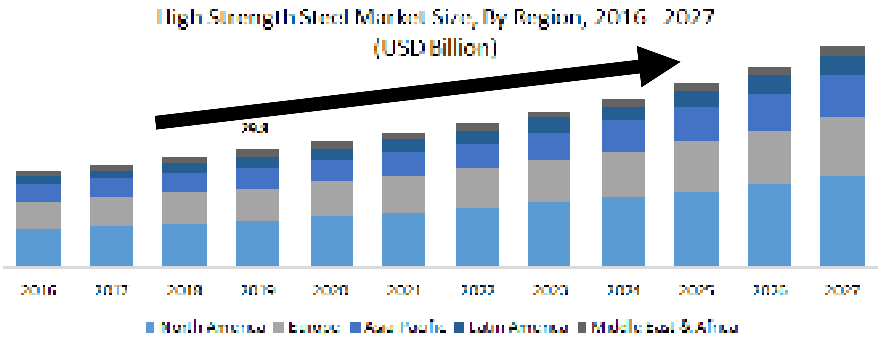
Current challenges in sheet metal forming

The use of lightweight materials is often connected to a loss in formability.

- Use of higher-strength (AHSS) and ultra-high-strength steel (UHS sheet materials to save material and therefore also weight
- Use of other lightweight materials (e.g. aluminum, magnesium)
- Significant increase in production of high-strength (AHSS) and ultrahigh-strength (UHSS) materials worldwide
- Applications mainly in automotive engineering, mechanical engineering and construction, but also in packaging
- **BUT:**
  - These materials are usually more difficult in forming processes
  - Failure in the forming process is therefore more likely



[ahssinsights.org]



[polarismarketresearch.com]

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Failure analysis and failure prediction is an essential part in the sheet metal forming process

- Approximately 1/3 of total forming tool costs in deep drawing are due to corrections during the run-in process
- Simulation of deep drawing processes with the aid of FEM (Finite Element Method) is therefore becoming increasingly important
- The aim is to produce faultless components and to prevent failure due to wrinkling and / or tearing

- Various material parameters are necessary in a simulation
- For the failure analysis of sheet metal materials:

FLC – Forming Limit Curve

[autoform.com]

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The forming limit curve (FLC) represents the failure behavior of a sheet metal material

General procedure:

1. Critical strain combinations are generated
2. Different strain states with variation of the widths (e.g. S40)
3. Comparison and evaluation of the results with deformation changes on components or in a simulation

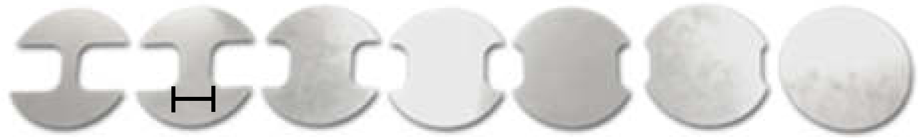
Determination of the forming limit curve (FLC) based on the major and minor strain in the

Forming Limit Diagram

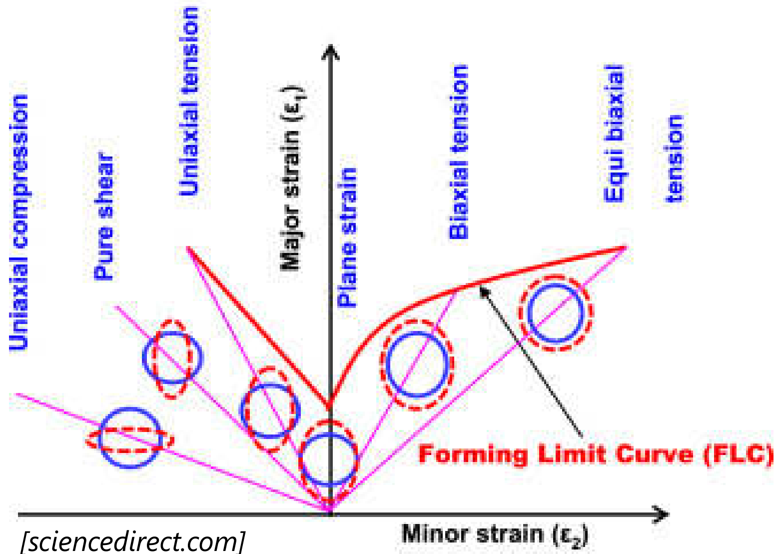
Anwendung der Grenzformänderungskurve:

- Inspection of incoming material or quality assurance
- Comparison of materials (suitability for the process?)
- Simulation (FEM) and analysis of failure behavior

Uniaxial strain *Biaxial strain*



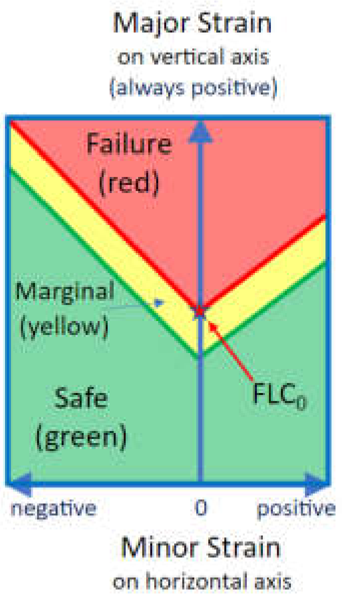
z.B. S40 (40 mm)



[sciencedirect.com]

The forming limit curve (FLC) describes the formability of sheet metal materials until to failure due to necking.

Major strain is defined as the strain in the direction of maximum elongation.



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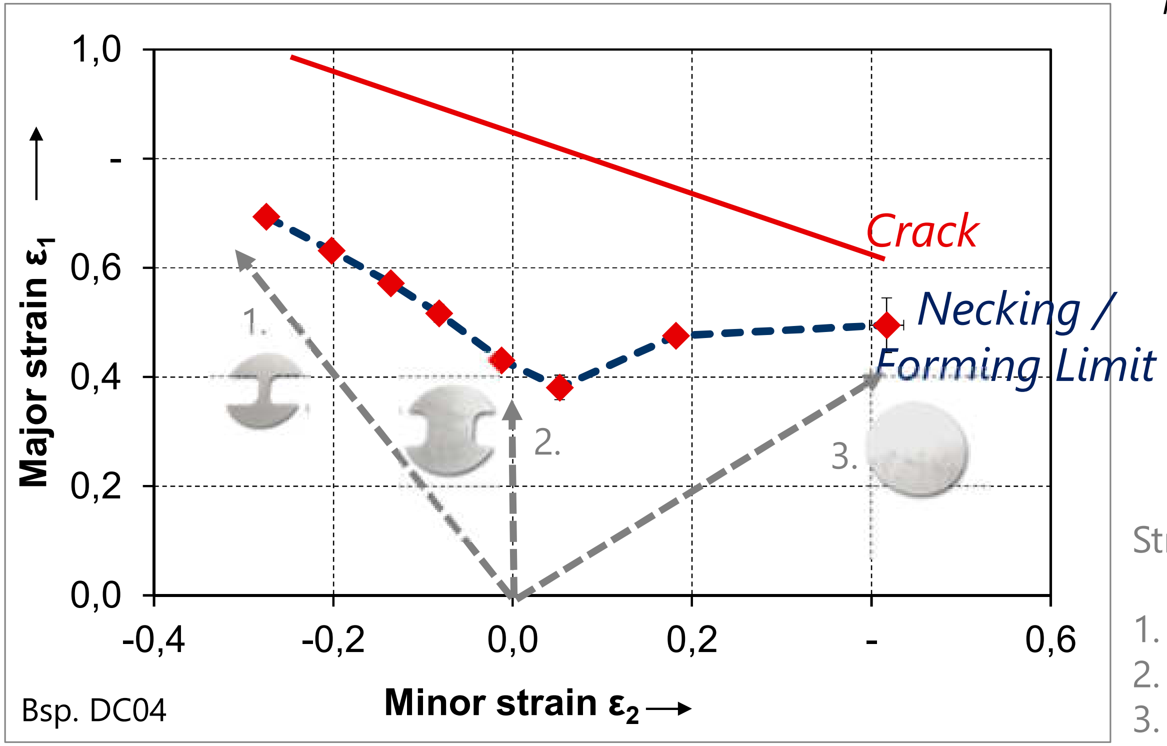
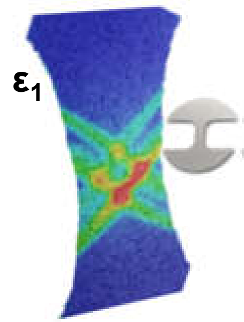


[Merklein, Schmid]

Minor strain is the strain perpendicular to the main strain

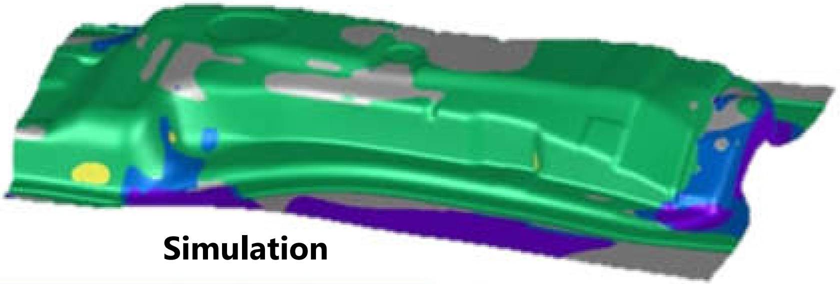


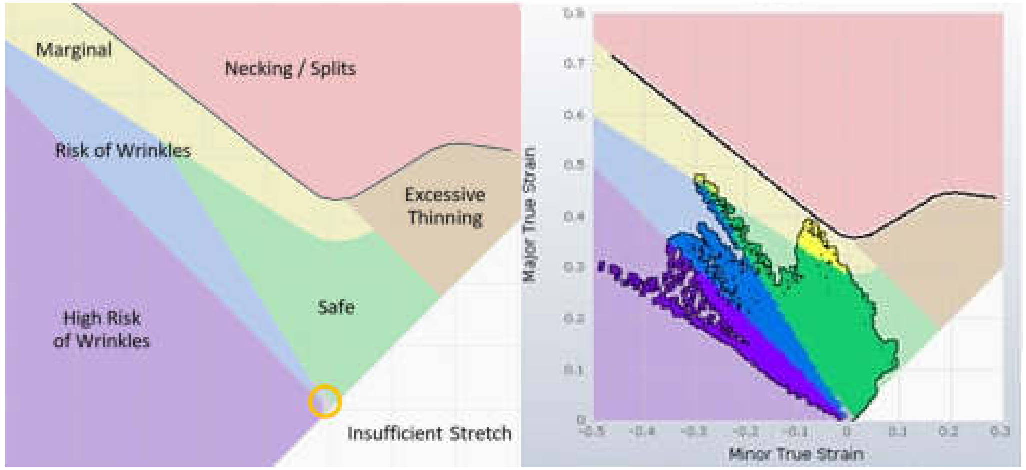
Strain states:

1. uniaxial strain
2. plane strain
3. biaxiality

The forming limit curve is used in a) forming simulations or b) in evaluation on already produced components.

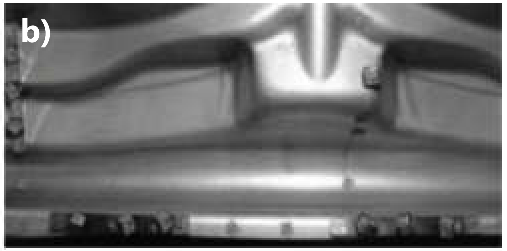
a)

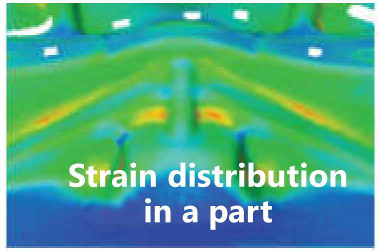


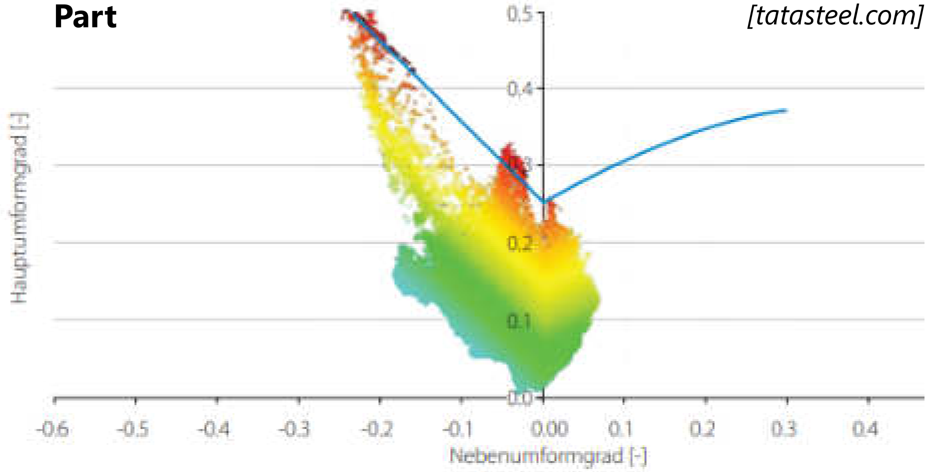


Forming simulation using FEM vs. FLC

[formingworld]







Strain distribution in a deep drawn component vs. FLC

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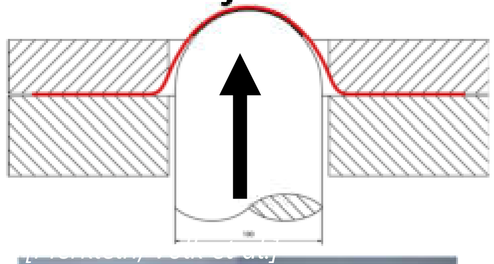
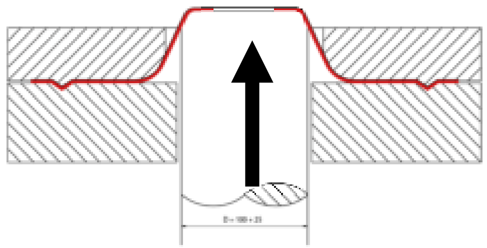
The determination of a forming limit curve for sheet metal materials is standardized by ISO.

- Use of Nakajima or Marciniak geometries
- Sheet thickness from 0.3 to 4.0 mm,
  – Recommendation: steel up to a maximum of 2.5 mm
- drawing speed 0.5 – 2.0 mm/s
- n = 3 specimens per geometry
- Frequency min. 10 images / mm
- Orientation to rolling direction according to standard depending on the material

Nakajima test

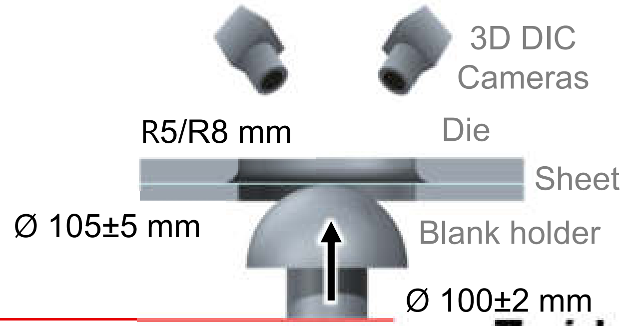


Marciniak test



Standards

- **DIN EN ISO 12004: Metallic materials - Determination of forming-limit curves for sheet and strip**
- ***Part 2: Determination of forming-limit curves in the lab***
- *Part 1: Measurement and application of forming-limit diagrams in the press shop*
- *ASTM E2218-15: Standard Test Method for Determining Forming Limit Curves*



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During the forming process the local strains on the sheet metal are analyzed using 3D DIC

Testing process according to ISO 12004-2:2021:

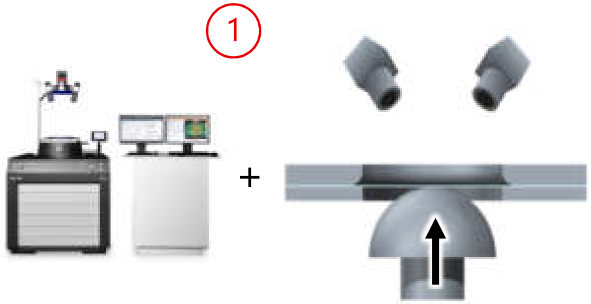
- Lubrication and preparation of specimens
- Clamping of specimen with blank holder

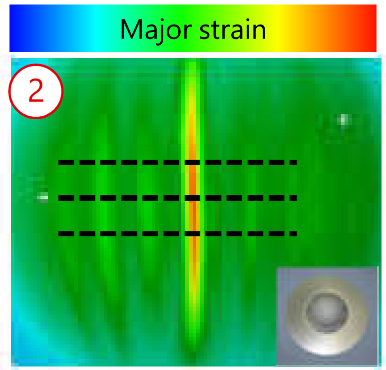
1 Specimen is formed with punch
  - No flow of the material from the side allowed
  - Recording of local strains up to the crack

2 The last image before crack is evaluated
  - Evaluation using section lines
  - Analysis of strain in the last image before crack

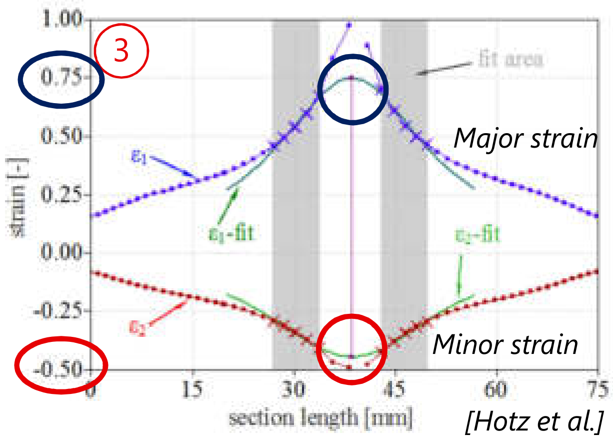
3 Re-calculation to necking according to standard

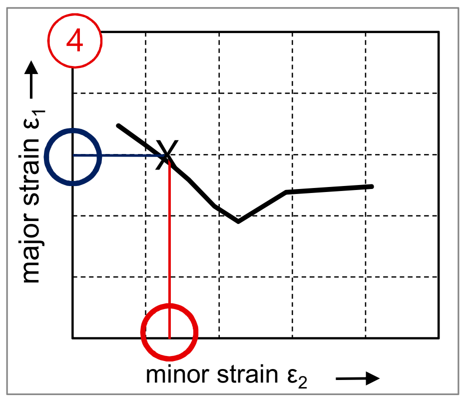
4 Transfer of $\varepsilon_1 - \varepsilon_2$ into the diagram





section lines





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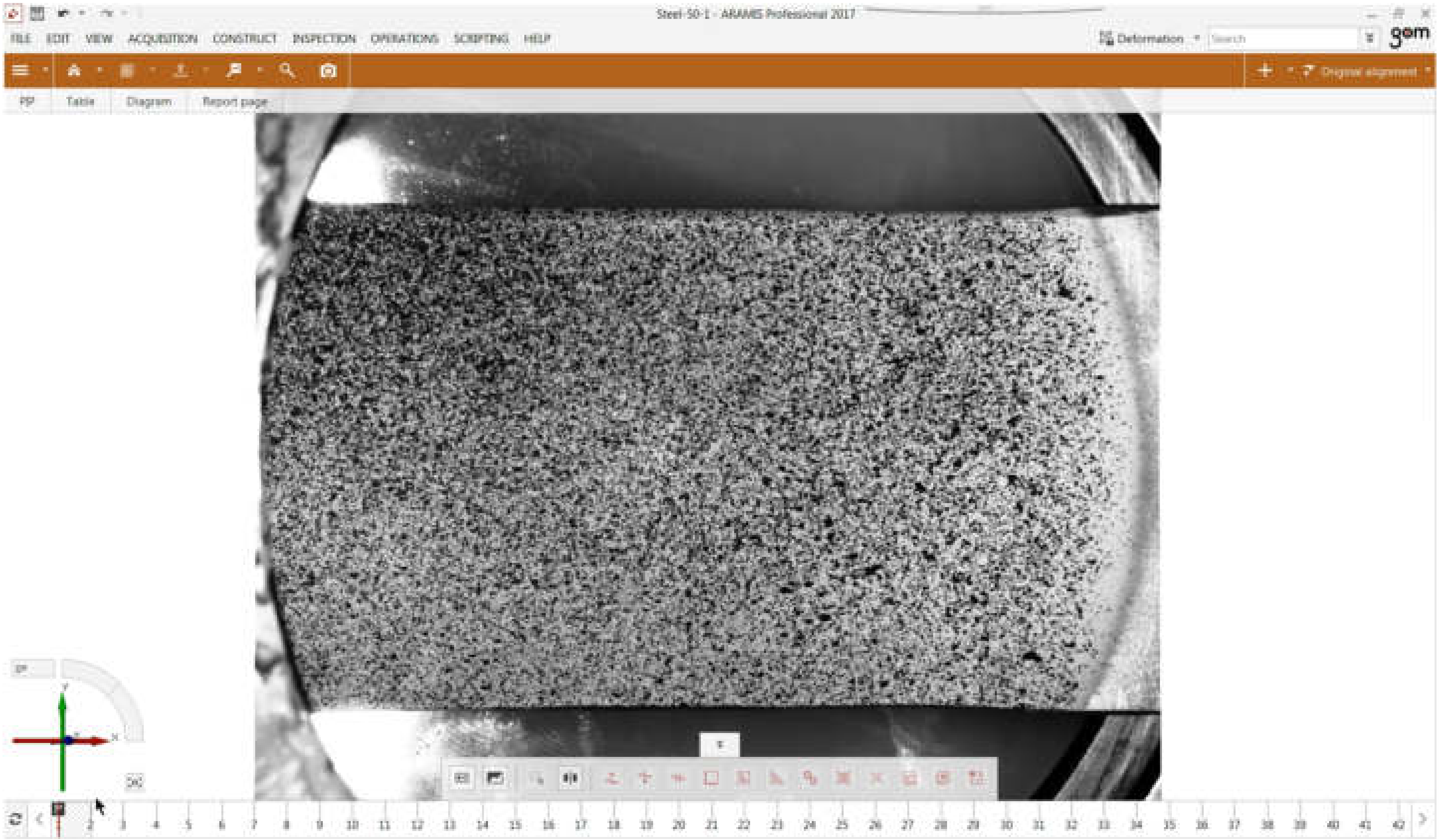
Video: Strain analysis to determine a forming limit curve



[GOM Zeiss]

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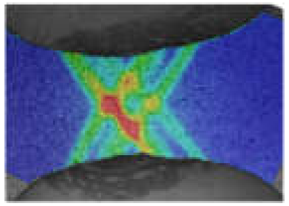
ZwickRoell offers an integrated solution for the analysis and determination of a forming limit curve.



1) Material testing machine

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- Sheet Metal Testing Machines BUP
- Specimen forming without material flow

2) Strain analysis

ZEISS

gom a ZEISS company

- Optical 3D DIC System
- Analysis of strains and calculation

3) Software

- ***testXpert* III**
- Digital interface for optimum use of ARAMIS, BUP testing machine and testXpert III

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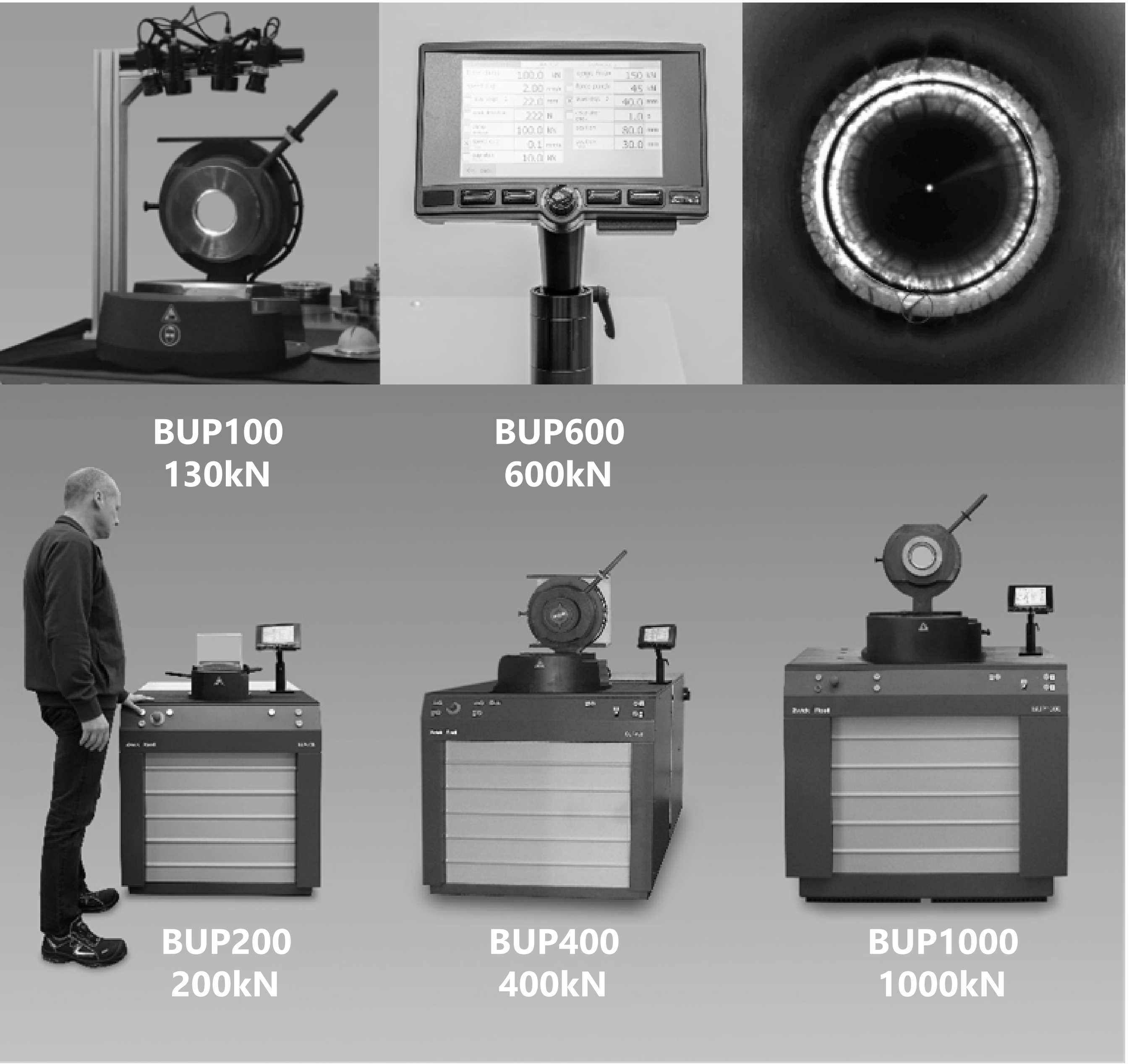

Sheet Metal Testing Machines BUP

BUP –

An all-rounder for the sheet metal testing and analysis

- Various applications
- Integrated functions such as blank holder, punching, pulling and ejecting
- Flexibility through simple and fast changes of forming tools

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The BUP: Ergonomic design coupled with sophisticated technology.

- **Drawing force from 130 kN to 1000 kN (depending on model)**
- Speed depending on the model 0.5-1200 mm/min (0.008-20 mm/s)
- **Control of the drawing speed and the blank holder force**
- Operation via display and / or testXpert software
- Simple and flexible exchange of tools
- The resolution of the travel is 0.001 mm
- The housing cover can be opened quickly.
- Safety due to 2-hand operation for closing / opening
- Key switch for switching between setup and test mode
- **The test tools of a BUP can be changed easily and quickly.**

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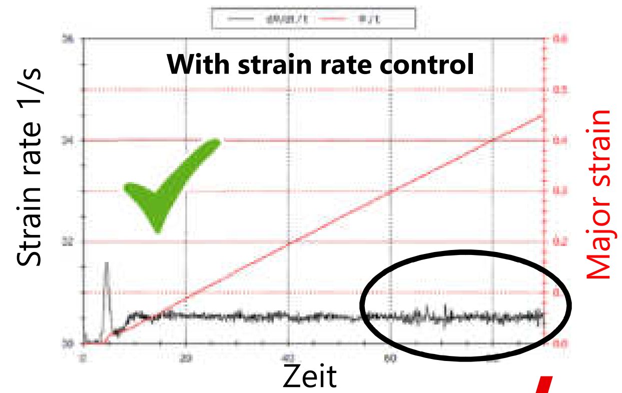
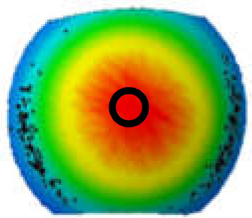
ZwickRoell offers a strain rate control for the BUP sheet metal testing machine as a further option.

- The strain rate influences the results of material testing for strain rate dependent materials (e.g. deep drawing steels DC).
  - During forming, material is thinning (also in FLC)
  - At constant drawing speed, the strain rate increases steadily
  - Specification in the standards often with constant speed

- Strain rate control using 3D DIC system and the digital interface with BUP testing machine



- Implementation already standardized in other tests
  - Tensile test according to DIN EN ISO 6892-1, method A1
  - Tensile test according to ASTM E8, method B (closed loop)



Evaluation area

- Strain rate control for strain rate sensitive materials

ZwickRoell sheet metal testing machines meet all requirements for testing of formability of sheet metal in accordance with the common standards and procedures.

Test method	Standard	BUP100/200	BUP400/600	BUP1000
Cupping test	DIN EN ISO 20482, ASTM E 643	X	X	X
Earing test	SWIFT, EN 1669, ISO 11531	X	X	X
FLC	ISO 12004	on request	X	X
Bulge	DIN EN ISO 16808	X	X	X
LDH	n/a	X	X	X
Springback test	n/a	X	X	X
Engelhard test	n/a	X	X	X
Fukui test	JIS-Z-2249	X	X	X
Swift	n/a	X	X	X
Hole expansion	KWI, ISO 16630	X	X	X
Coatings test	DIN EN ISO 1520	X	X	X
U-Bead test	n/a	X	(X)	(X)
…	…	X	X	X
Customized test	n/a	X	X	X

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The forming limit curve is used to analyze and predict the failure behavior of sheet metal materials.

- The trend towards lightweight materials continues - the forming process gets more difficult as a consequence.
- The forming limit curve is and remains the way to go for failure analysis for sheet metal materials.
- The test procedure and evaluation are internationally standardized.
- A comparison with simulation data or real components is possible.
- ZwickRoell offers a solution in cooperation with GOM ZEISS. The 3D DIC system can be easily integrated.
- Further functionalities in the BUP are available.

BUP family – final components and in production

The BUP can be explored with an implemented 3D DIC system in the metal center.

Literature and sources (selection)

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