Aalen University

Determination and Optimisation of a Temperature-Dependent-Failure curve for High-Strength Aluminium Alloys applicable for Hotforming

15th Deutsches LS-DYNA Forum

Bamberg, 15.-17.10.2018

Julian Schlosser

Agenda

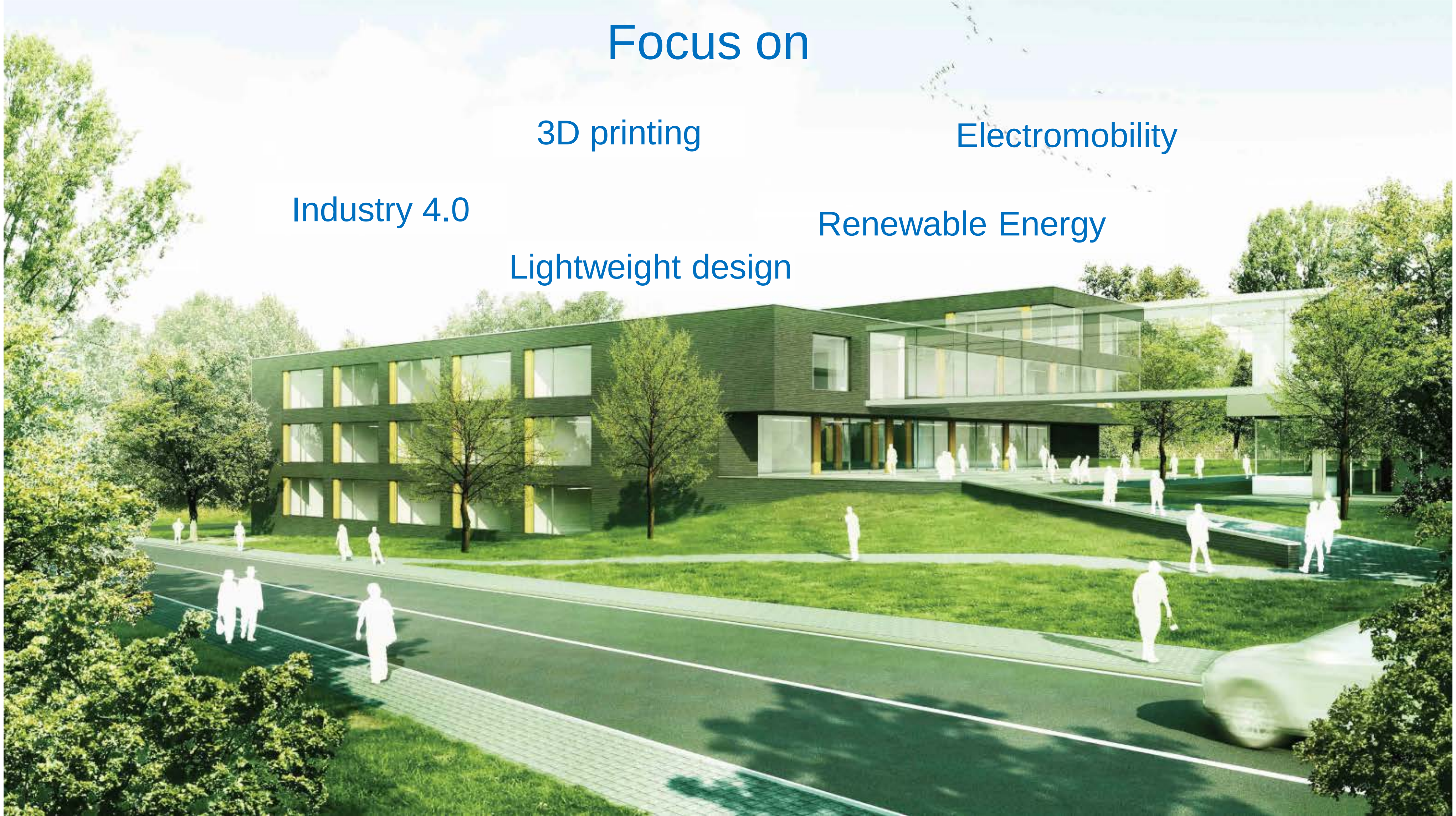
- Introduction
  - Aalen University
  - Lightweight Technology Centre (TZL)
- General information about aluminium
- Preliminary investigation on AA7075-T6 material
  - Why failure models are important for FEM-simulation
  - Determination and numerical calibration of the material parameters for TFC
  - Example of a Triaxial-Failure Curve (TFC)
- Hotforming process for high strength aluminium alloys
  - Determination of material parameters for the Hotforming process
  - Material modelling of AA7075 in the Hotforming process using MAT_BARLAT_YLD2000
  - Numerical calibration of the failure-curve using parameter optimisation
- Summary

Facts and Figures

- About 5.800 Students
- 18 Bachelor Programs
- 20 Master Programs
- plus additional part time programs (further education)
- 148 professors
- 151 research staff
- 239 administrative assistants

Aalen University

Start of construction of new research building in 2017
Invest of 25 million Euro



Lightweight Technology Centre (TZL)

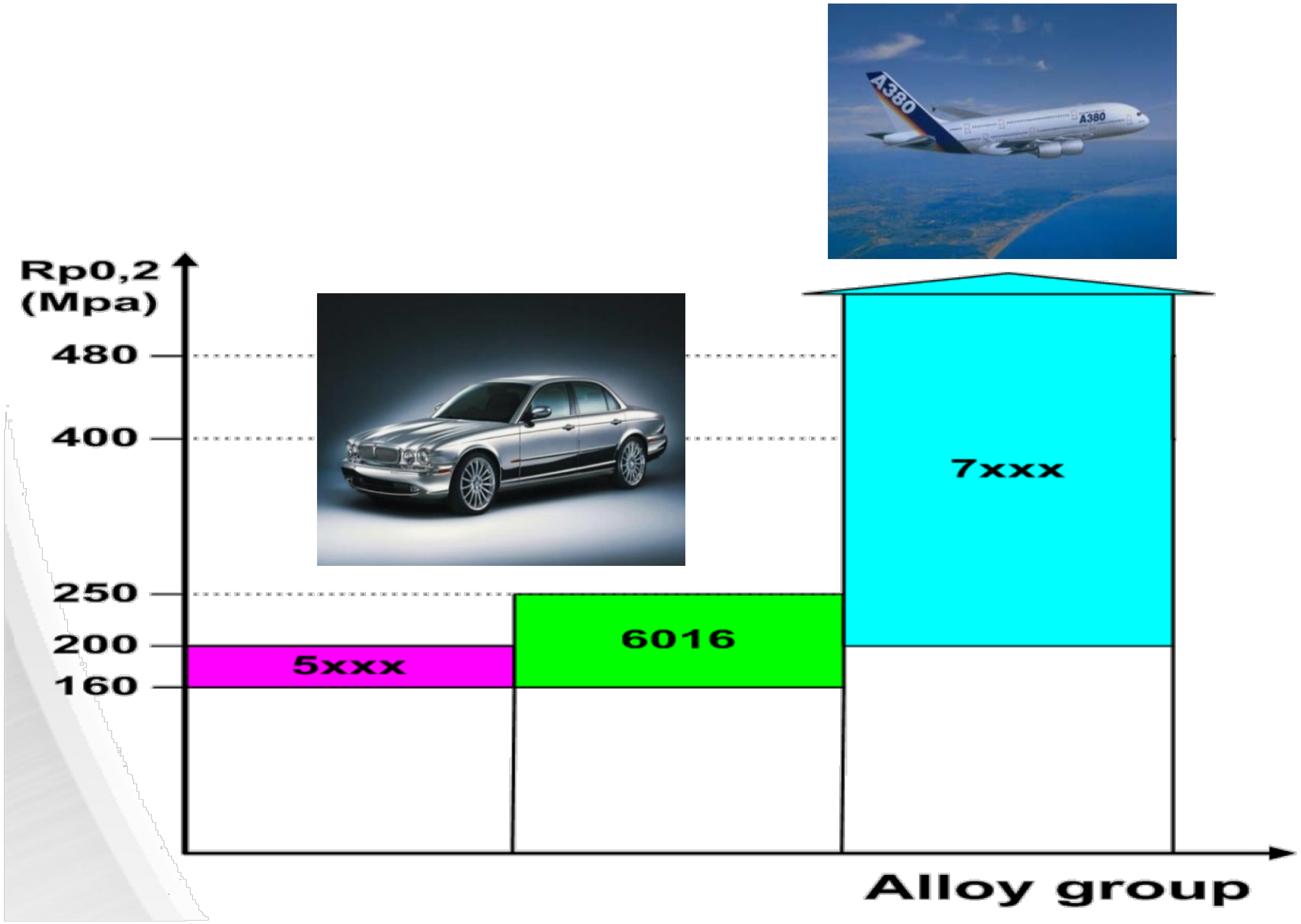
- Founded by
  - Aalen University
  - Schwäbisch Gmünd
    - University of Design
    - City of Schwäbisch Gmünd
    - Research institute of noble metals and metal chemistry

- Focus on Structure optimisation in particular Topology optimisation
  - Topology optimisation is a computer-aided method for determining the optimised component shape in combination with a reduction of weight and volume.

Lightweight Technology Centre (TZL) Research

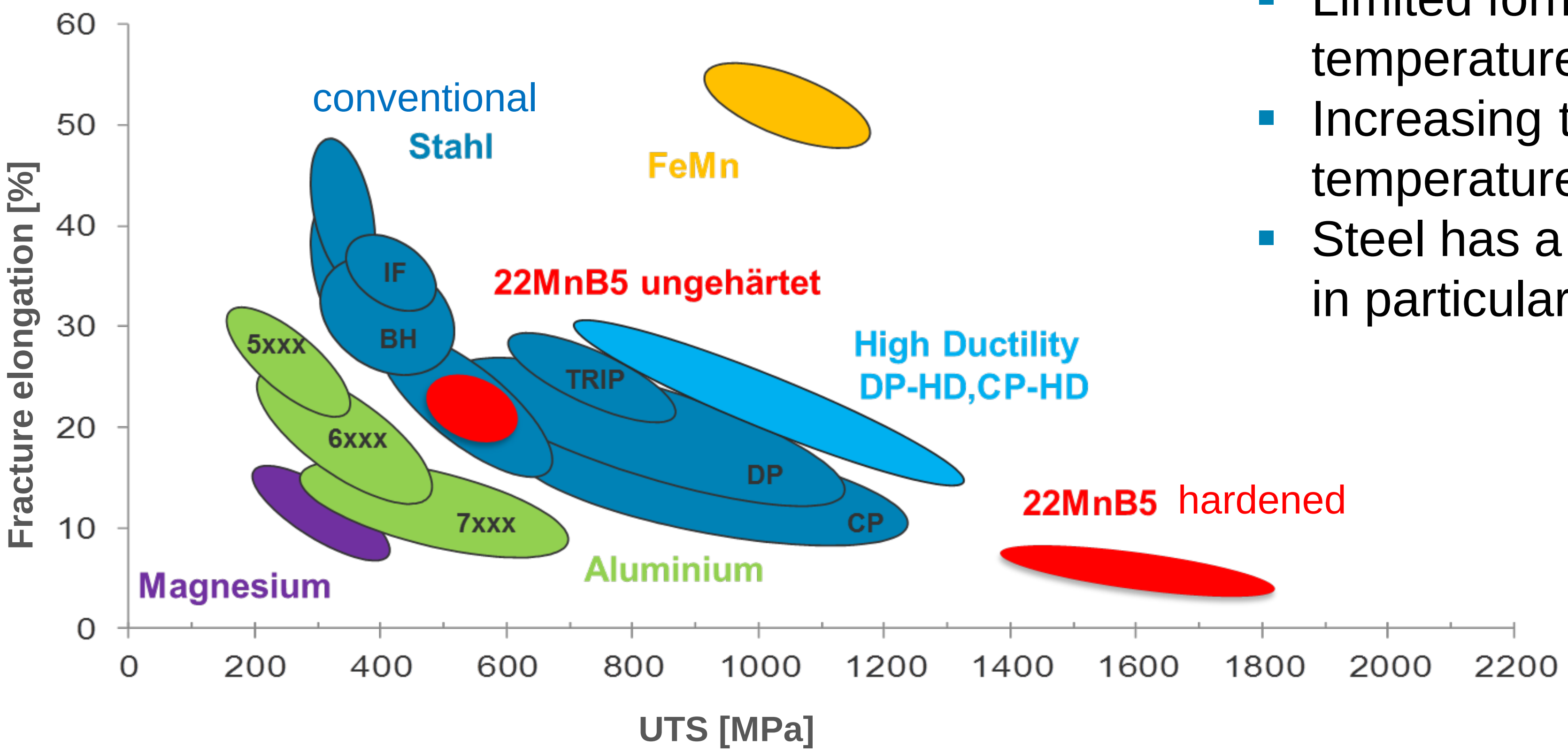
- Benchmark investigation about different Topology optimisation Software
- Dyn. Topology optimisation for crashrelevant components by adding CFK Patches
- Optimisation of Energy Conversion
- Result of topology optimisation (STL) → 3D model (Step)
- Production restrictions for 3D printing in topology optimisation
- Hotforming & Crash simulation
- Material modelling
- Damage- / Failure modelling

General information about aluminium



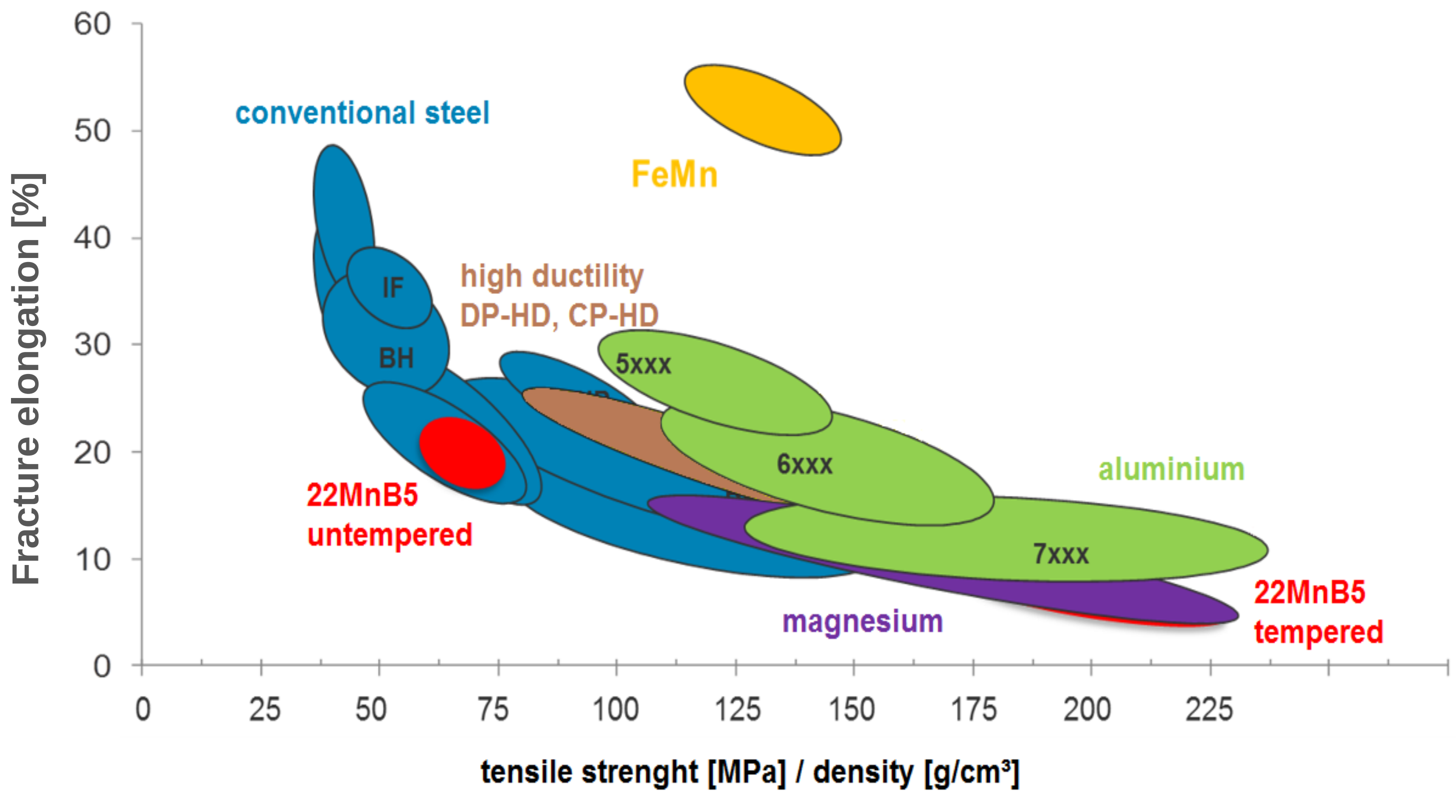
- Lightweight design with aluminium
  - Aerospace has been using high-strength aluminium alloys for many years
  - More and more of these alloys are also used in the automotive sector
- Improving the deformability by the Hotforming technology
- Additional lightweight potential by using new high strength aluminium alloys of type 6082, 7021, 7075

General information about aluminium



- Limited formability at ambient temperature
- Increasing the formability at elevated temperatures
- Steel has a higher strength,
  in particular press hardened steel

General information about aluminium



- Aluminium has a lower density (2.7 g/cm^3) as steel (7.85 g/cm^3)
- Lightweight construction potential is exemplified by the specific strength (ratio of strength and density)

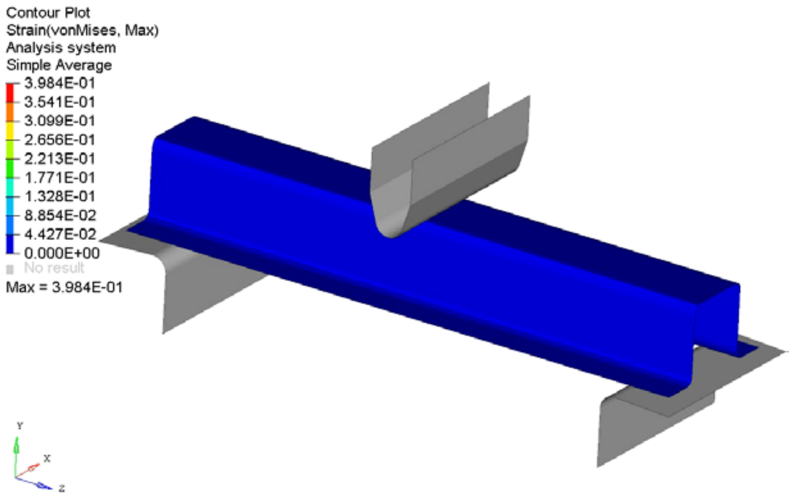
→Aluminium alloys offer higher specific strengths than press hardened steels

→High strength aluminium alloys provide higher lightweight potential for the use in car body constructions

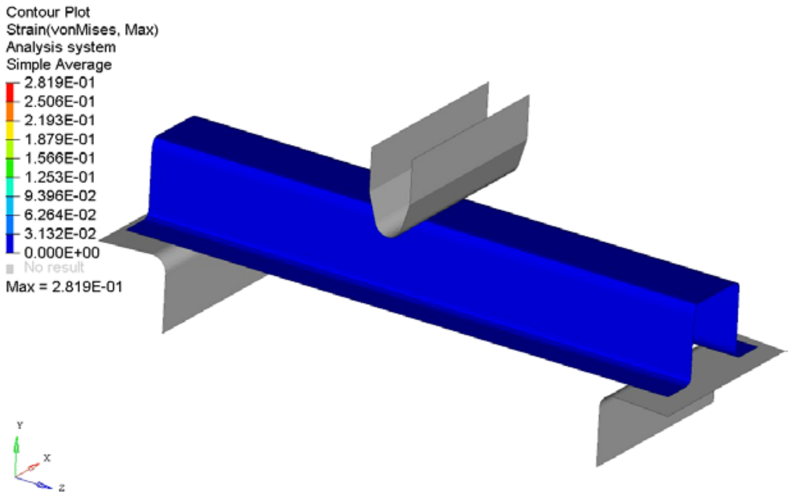
Preliminary investigation on AA7075-T6 material

- Why damage and failure modelling is important?
- Illustration is based on a dynamic 3-point bending test using AA7075-T6 (Hill48)

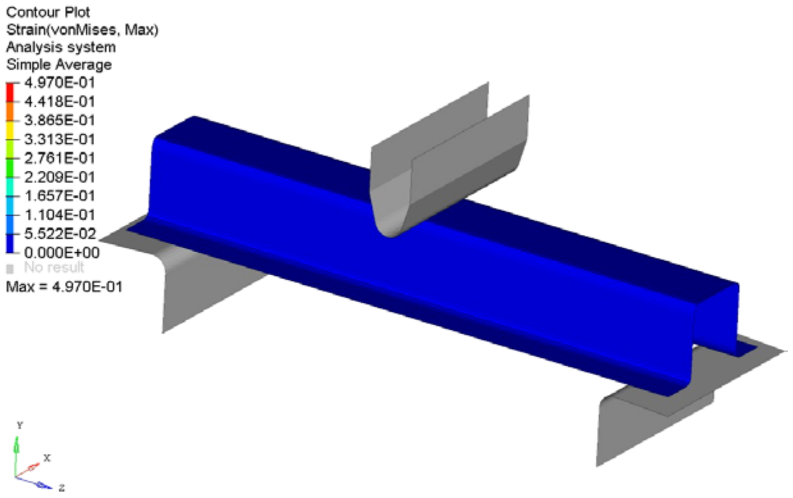
without failure model	using max. tensile plastic strain for failure modelling	GISSMO for failure modelling



max. force punch: 32.2 kN



max. force punch : 28.0 kN



max. force punch: 29.9 kN

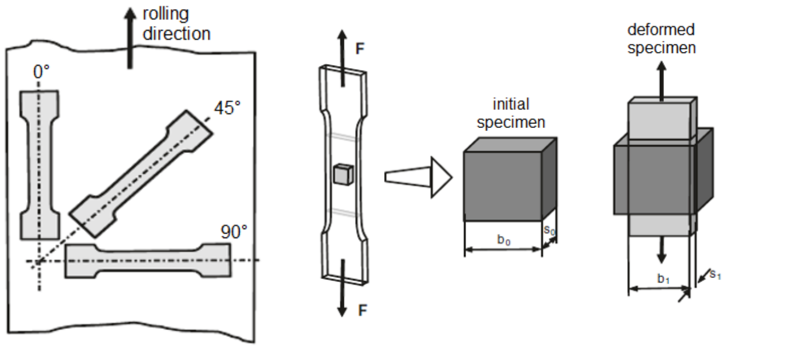
→ For a good crash simulation it's necessary to use suitable material-, damage and failure models

Preliminary investigation material modelling of AA7075-T6

- Anisotropic 2D-material models

Model	σ_0	σ_{45}	σ_{90}	r_0	r_{45}	r_{90}	σ_b	r_b	Parameter
Hill ´48	X	-	-	X	X	X	-	-	4
Hill ´90	X	-	-	X	X	X	X	-	5
Barlat ´89	X	-	-	X	X	X	X	-	5
Banabic 2005	X	X	X	X	X	X	X	X	8
Barlat 2000	X	X	X	X	X	X	X	X	8

- Lankford parameter ***r*** (DIN EN ISO 10113)



$$r = \frac{\varphi_b}{\varphi_s}$$

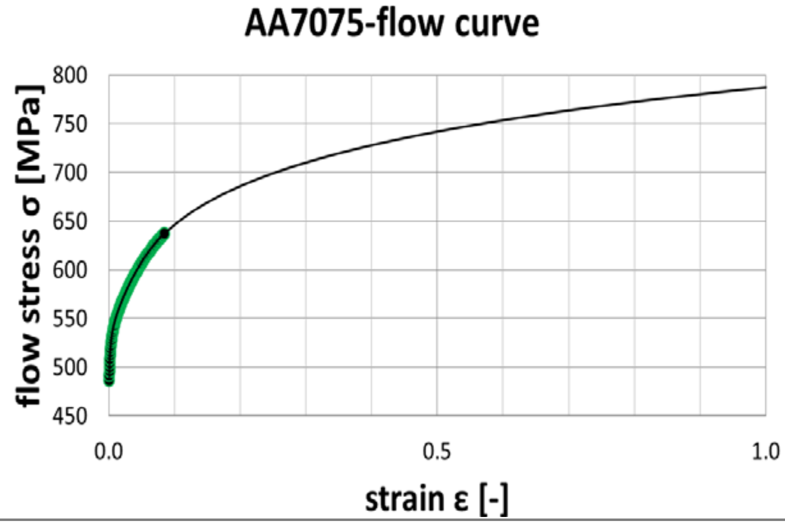
$$\varphi_b = ln\frac{b_1}{b_0}$$

$$\varphi_s = ln\frac{s_1}{s_0}$$

- Experimental results

extrapolation of the flow curve using Hollomon's law

$$\sigma = C \times \varepsilon^n$$

σ_f [MPa]	UTS [MPa]	e_{20} [%]	Flow curve
487	548	17	

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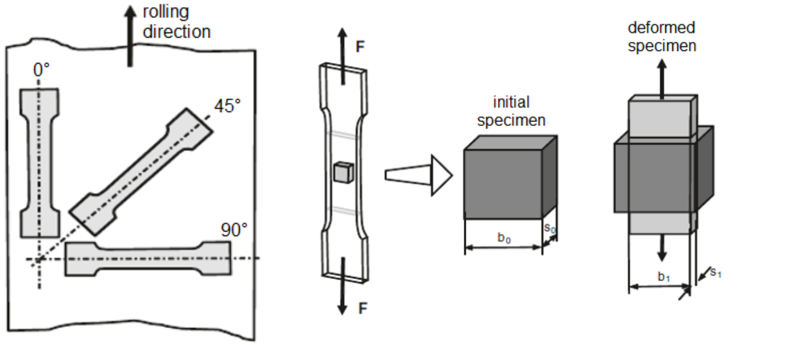
- Lankford parameter ***r*** (DIN EN ISO 10113)



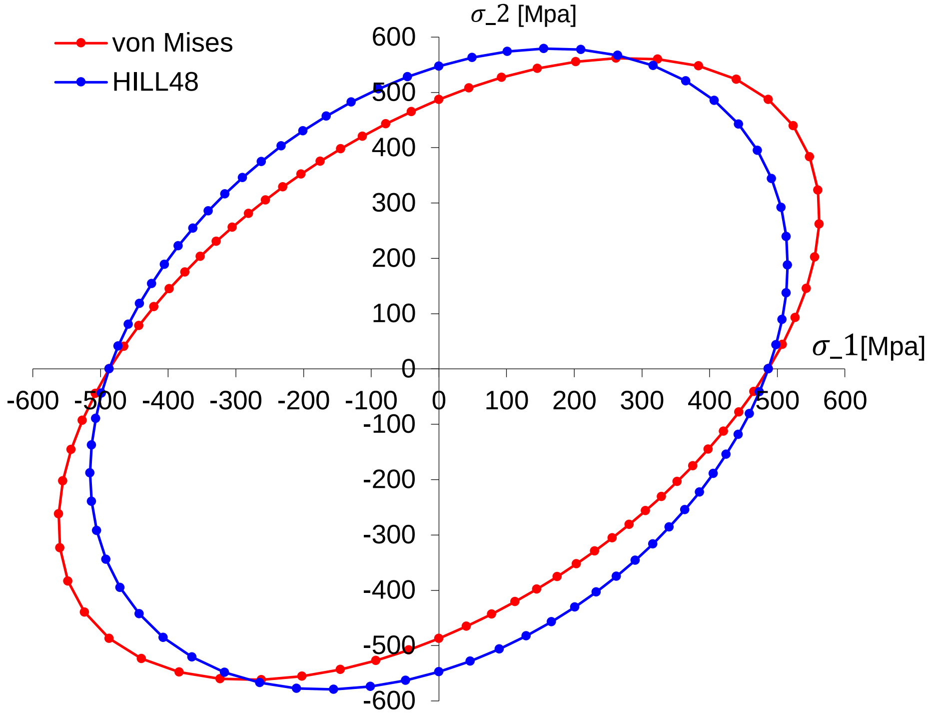
$$r = \frac{\varphi_b}{\varphi_s}$$

$$\varphi_b = ln\frac{b_1}{b_0}$$

$$\varphi_s = ln\frac{s_1}{s_0}$$

- Experimental results

flow locus curve



Lankford parameters

$$r_0 = 0{,}410 \; ; \; r_{45} = 0{,}721 \; ; \; r_{90} = 0{,}581$$

Small description of failure model GISSMO

- LS-DYNA MAT_ADD_EROSION (GISSMO)
- The failure model describes a strain failure model based on path-dependent damage accumulation using user-defined function
- In sheet metal forming it is a common assumption to use the plane stress case ($\sigma_3 = 0$). Consequently, the hydrostatic stress σ_m and the von Mises stress σ_{vm} are:

$$\sigma_m = \frac{\sigma_1+\sigma_2}{3} \quad ; \qquad \sigma_{vm} = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 * \sigma_2}$$ and the triaxiality $\eta = \frac{\sigma_m}{\sigma_{vm}}$

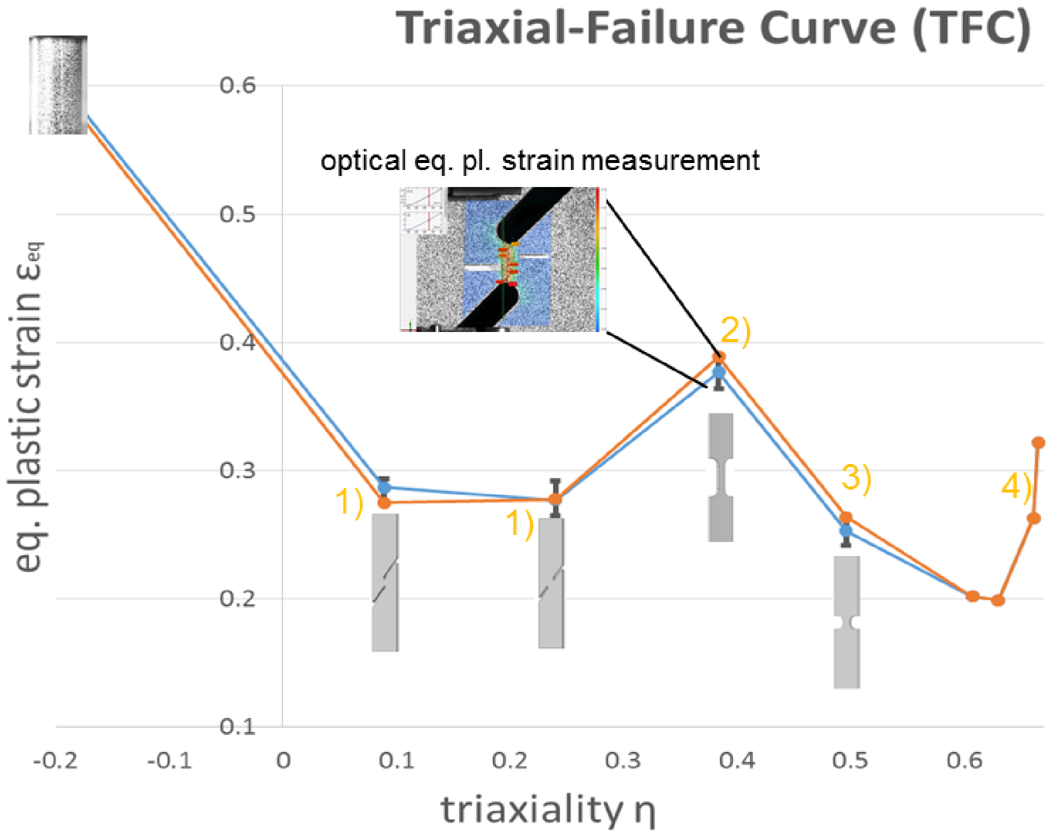
- The damage accumulation rule is given by:

$$\Delta D = \frac{\Delta\varepsilon_p}{\varepsilon_f} * n * D^{\left(1-\frac{1}{n}\right)}$$

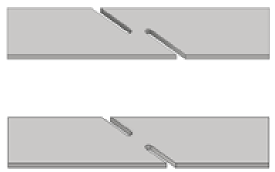
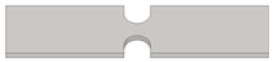
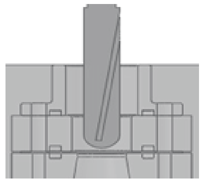
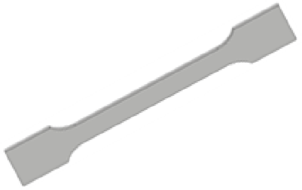
- The damage rule is evaluated and accumulated at every time step using the current value of damage (D), plastic strain increment ($\Delta\varepsilon_p$) and the equivalent fracture strain ($\varepsilon_f(\eta)$) as function of the triaxiality. A crack or element rupture occurs, if the damage parameter D is reached one.
- The failure strain is obtained by different tensile test geometries to reach various triaxiality and can be implemented into the simulation program by a Triaxial-Failure-Curve (*TFC*)

Example of a Triaxial-Failure Curve (TFC)

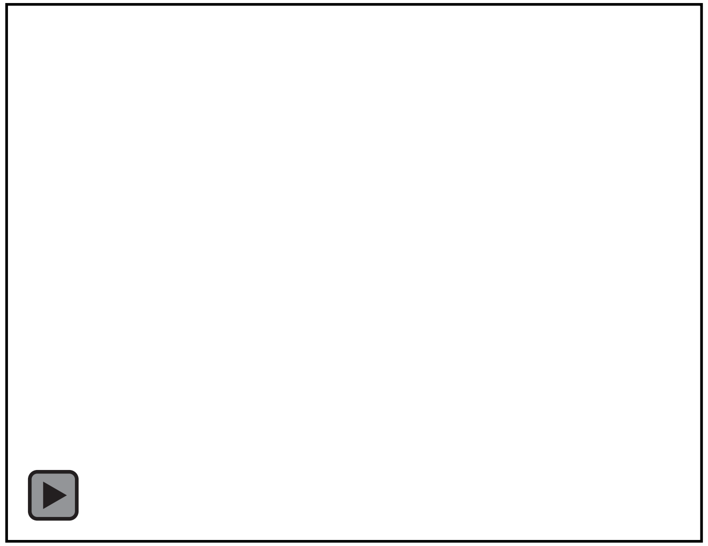
2D Shell - Material Investigations



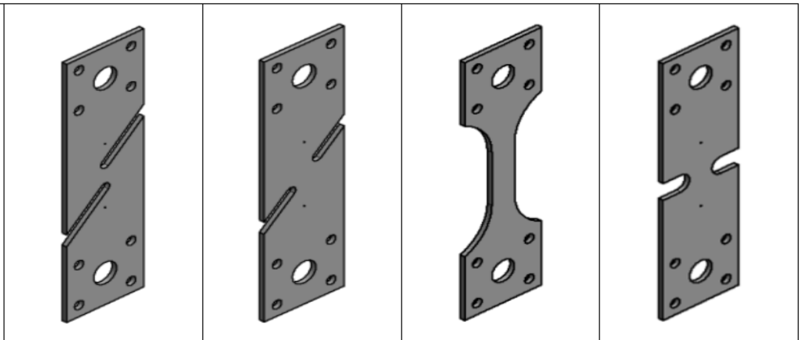
Following specimens are used to reach different triaxialities (various load states)

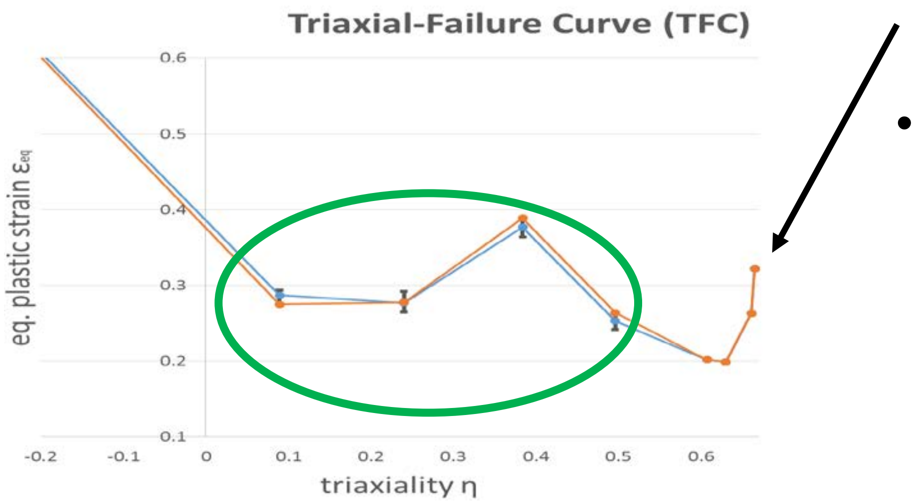
1	Shear test (various shear angles)	
2	Small-tensile test	
3	Notched test	
4	Erichsen, Bulge or Nakajima test	
5	Large-tensile test (for element regularisation)	

Determination of the Triaxial-Failure-Curve (*TFC*)



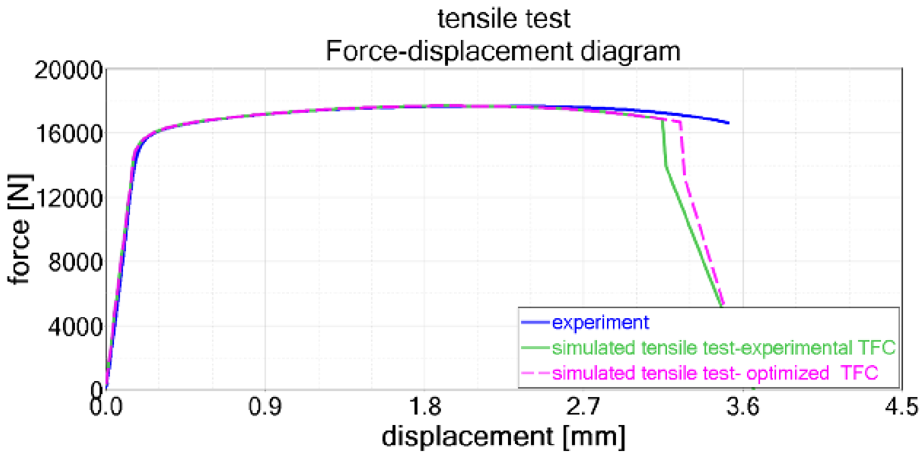
- Measurement of local equivalent strain at fracture for each specimen
- To determine the average triaxiality at fracture a simulation with each specimen-type has been carried out

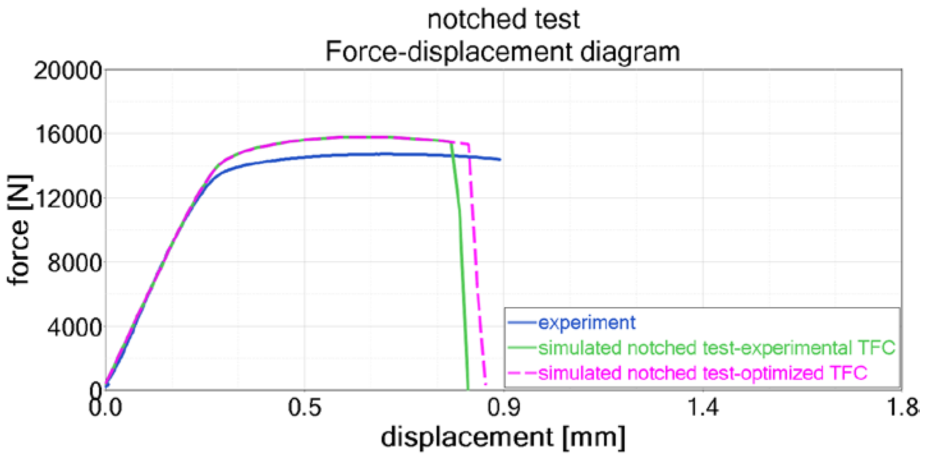
								
specimens	Shear 0°		Shear 15°		Tensile		Notched	
Test results	$\varepsilon_{eq.}$	η	$\varepsilon_{eq.}$	η	$\varepsilon_{eq.}$	η	$\varepsilon_{eq.}$	η
	0.287	0.089	0.277	0.240	0.377	0.384	0.253	0.496

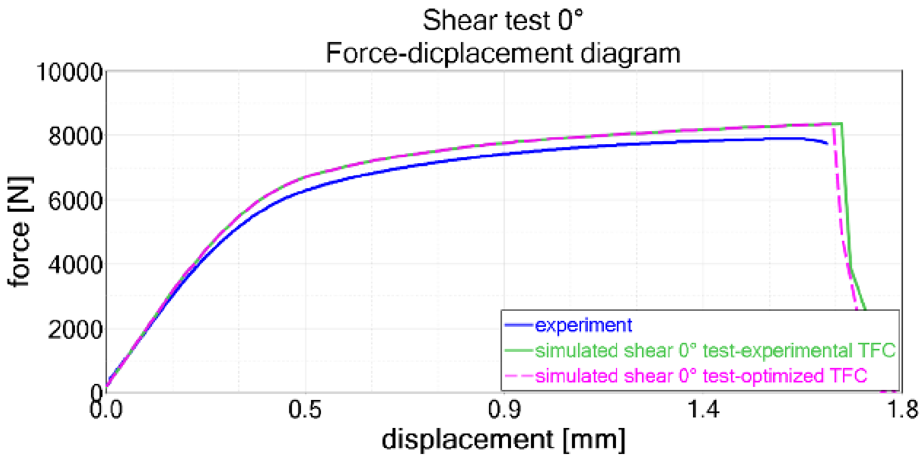


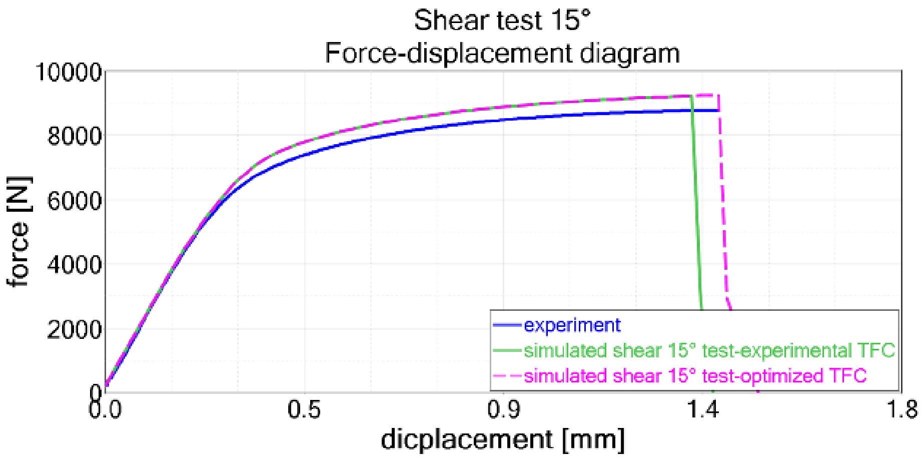
- To get values in this biaxial area an Erichsen, Bulge or Nakajima test is required
- Usually the metal forming industry has Forming Limit Curves (FLC) → these can be converted into TFC curves

Numerical calibration of the Triaxial-Failure-Curve using parameter optimisation





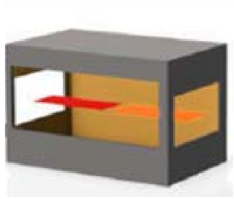
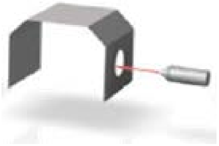
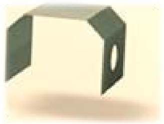




Schematic representation of the Hotforming process

Hotforming of high strength aluminium alloys

*source: voestalpine Automotive Components

allocation of the blanks at the press line	solution annealing T ≥ 465°C and quenching	forming at elevated temperatures ~200°C	cutting	ageing
				
AA6xxx/ AA7xxx in O / T4 condition	heating unit/ furnace	soft material→reduced forming forces temperature resistant lube	tool or laser cutting	PB cycle 185°C / 20min T79 condition

- Good formability of components with complex shapes
- Small springback
- Temperature resistant lubricants required
- Forming process can be simulated with FEM-simulation (material behaviour depends on temperature)
- Tool coating required because of adhesion effects
- Precooling treatment of the aluminium alloy using cooling station

Determination of material parameters for Hotforming process

Test setup to determine mechanical behaviour of AA7075 in the Hotforming process

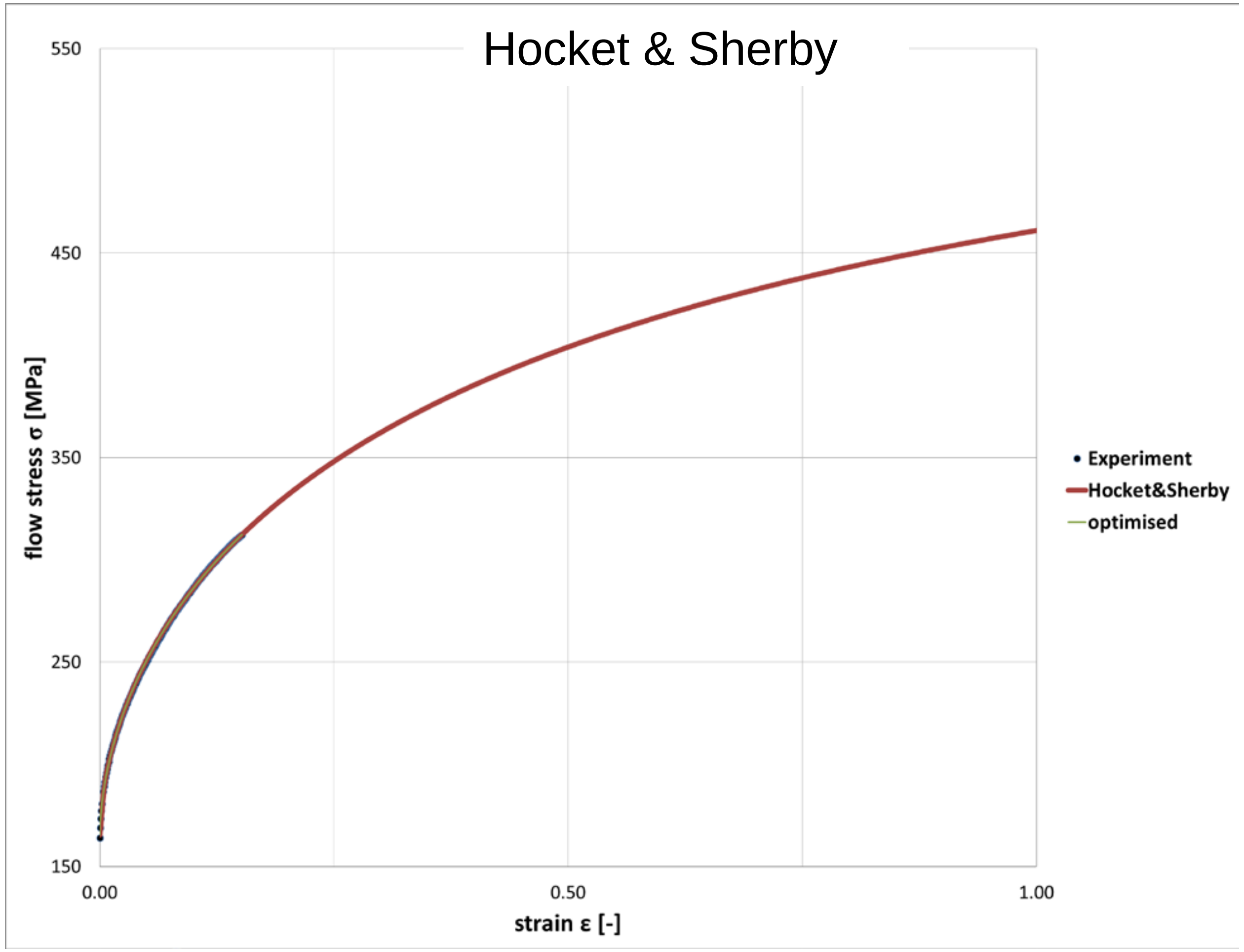
Press with 20 to
- Plate tool with two heating zones
- Integrated heating and cooling zones

Furnace
- Heating of the specimens to solution temperature

Tensile testing machine with furnace
- Integrated optical measurement system

Temperature monitoring for:
- Specimens
- Furnace
- Plates
- Oven
- Clamping jaws

Material modelling of AA7075 in the Hotforming process using MAT_BARLAT_YLD2000



Extrapolation of the flow-curve using Hocket-Sherby equation:

$$K_f = a - be^{-c\varepsilon_p^q}$$

Calculation with Excel (least squares method)

$$K_f = 556 - 391e^{-1.41\varepsilon_p^{0.58}}$$

a	b	c	q	A*
556	391	1.41	0.58	8

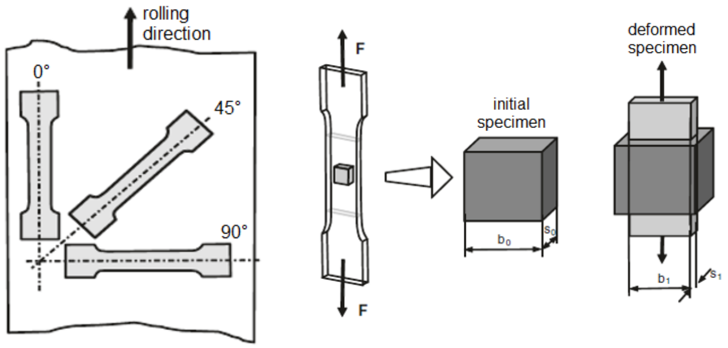
*For face centered cubic (FCC) A=8 is recommended by Logan and Hosford (1980)

Material modelling of AA7075 in the Hotforming process using MAT_BARLAT_YLD2000

- Anisotropic 2D-material models

Model	σ_0	σ_{45}	σ_{90}	r_0	r_{45}	r_{90}	σ_b	r_b	Parameter
Hill ´48	X	-	-	X	X	X	-	-	4
Hill ´90	X	-	-	X	X	X	X	-	5
Barlat ´89	X	-	-	X	X	X	X	-	5
Banabic 2005	X	X	X	X	X	X	X	X	8
Barlat 2000	X	X	X	X	X	X	X	X	8

- Lankford parameter ***r*** (DIN EN ISO 10113)



$$r = \frac{\varphi_b}{\varphi_s}$$

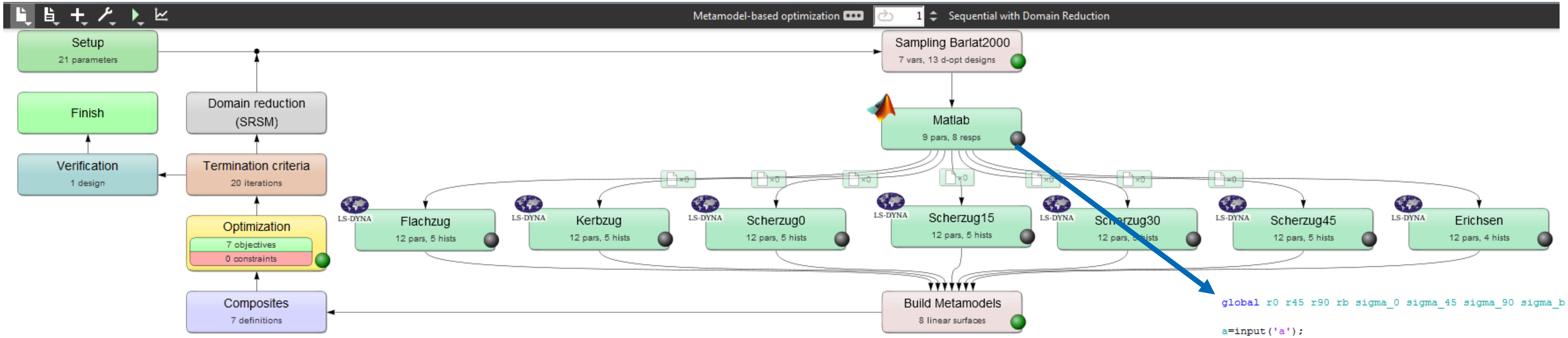
$$\varphi_b = ln\frac{b_1}{b_0}$$

$$\varphi_s = ln\frac{s_1}{s_0}$$

Lankford parameter	value
r_0	0.44
r_{45}	0.865
r_{90}	0.36
σ_0	203 MPa
σ_{45}	194 MPa
σ_{90}	204 MPa

→ Two more parameters are needed for Barlat-YLD2000

Material modelling of AA7075 in the Hotforming process using MAT_BARLAT_YLD2000

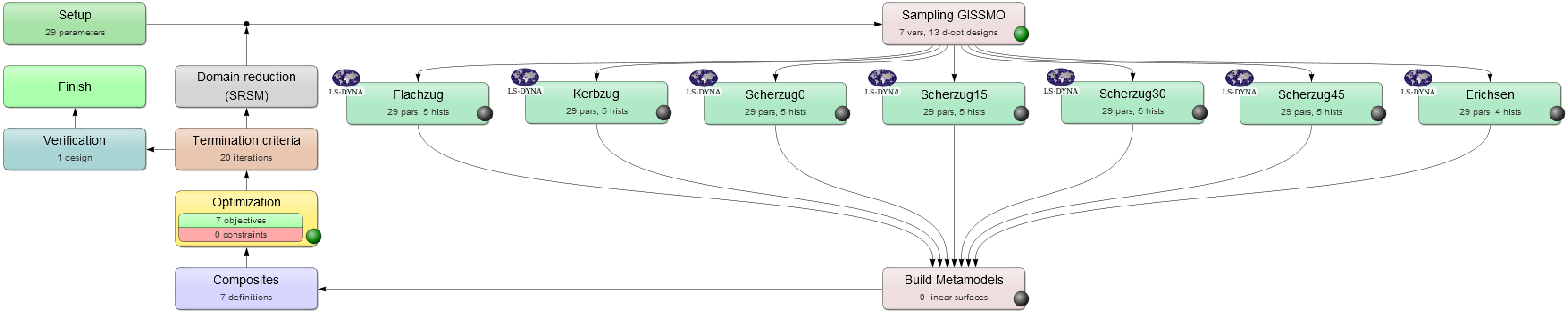



```
global r0 r45 r90 rb sigma_0 sigma_45 sigma_90 sigma_b a

a=input('a');
r0=input('r0');
r45=input('r45');
r90=input('r90');
rb=input('rb');
sigma_0=input('sigma_0');
sigma_45=input('sigma_45');
sigma_90=input('sigma_90');
sigma_b=input('sigma_b');


zg=[1 ; 1 ;1 ;1 ;1 ;1];
z=fsolve(@yld2000_1,zg);


xg=[1 ;1 ];
x=fsolve(@yld2000_2,xg);

alpha1=z(1);
alpha2=z(2);
alpha3=z(3);
alpha4=z(4);
alpha5=z(5);
alpha6=z(6);
alpha7=x(1);
alpha8=x(2);
```

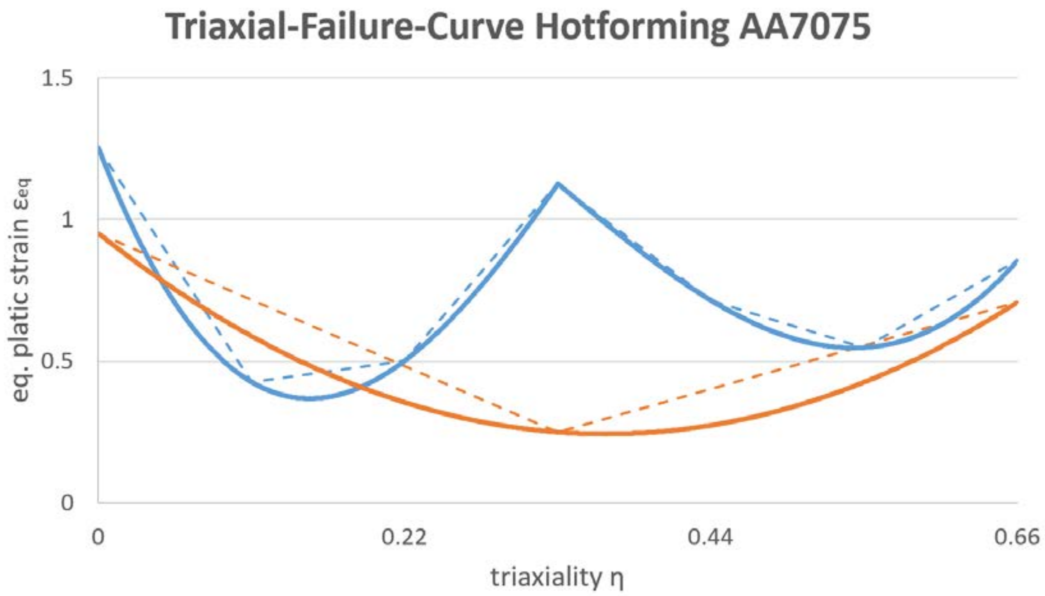
- Using parameter optimisation (LS-Opt) to identify the biaxial values
- Normalisation of the yield stresses and r-values
- In the Matlab script the alpha values will be calculated using Barlat-YLD2000 equations

α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
0.861	1.080	2.292	1.318	0.959	0.656	1.030	0.781

Numerical calibration of the Triaxial-Failure-Curve using parameter optimisation

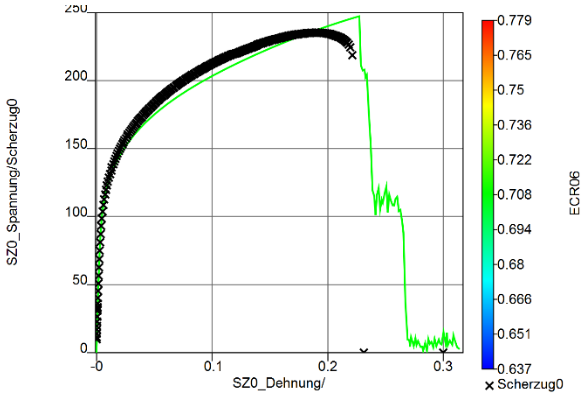


- Using parameter optimisation (LS-Opt) to identify the Triaxial-Failure-Curve and the Instability-Curve

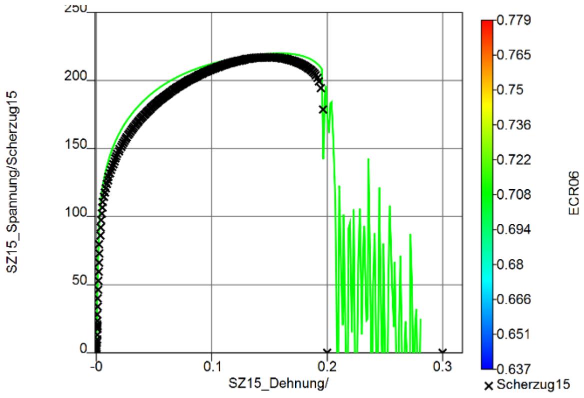


Numerical calibration of the Triaxial-Failure-Curve using parameter optimisation

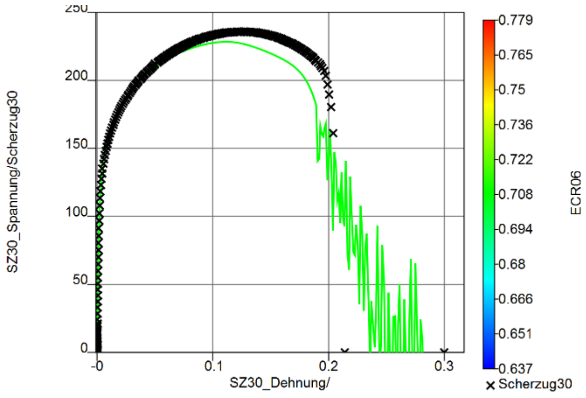
Shear 0°



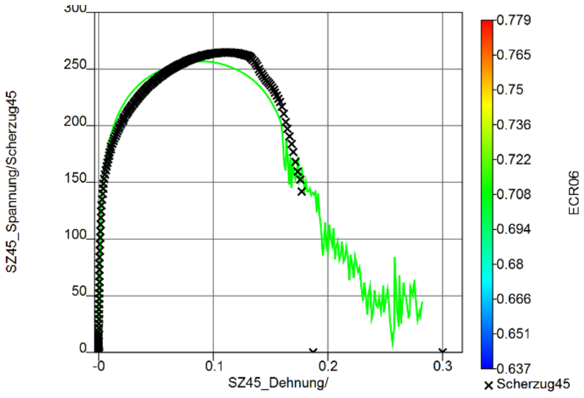
Shear 15°



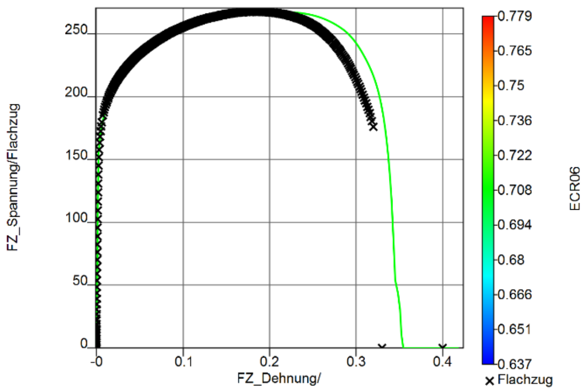
Shear 30°



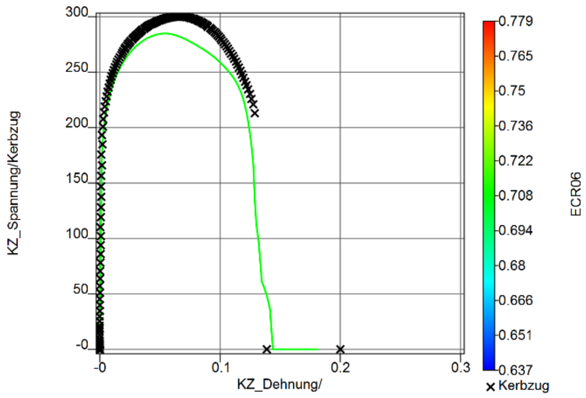
Shear 45°



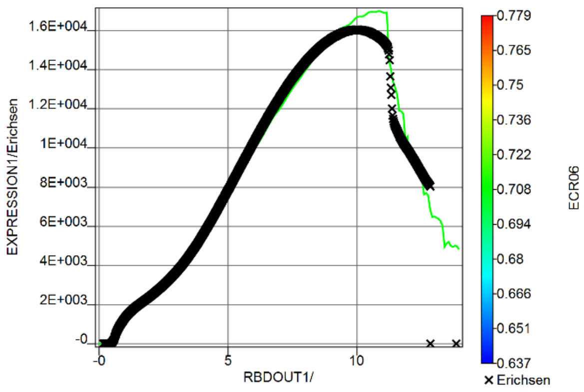
Tensile



Notched



Erichsen



Summary

- Experimental tests with various specimen geometries were carried out to determine the force-displacement characteristics of AA7075 material in the Hotforming process
- Material modelling of AA7075 in the Hotforming process using MAT_BARLAT_YLD2000
- The local strains at fracture have been monitored under different stress conditions ($0 < \eta < 2/3$) using an adapted optical measurement system
- A Triaxial-Failure-Curve and Instability-Curve were optimised and fitted to experimental data using parameter optimisation methods
- The predicted force-displacement data show good correlation with experimental results for all loading states.

Next step