Development, implementation and Validation of 3-D Failure Model for Aluminium 2024 for High Speed Impact Applications

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Development, Implementation and Validation of 3-D Failure Model for Aluminium 2024

Introduction

- **FAA William J Hughes Technical Center (NJ) conducts a research project to simulate failure in aeroengines and fuselages, main purpose is blade-out containment studies**

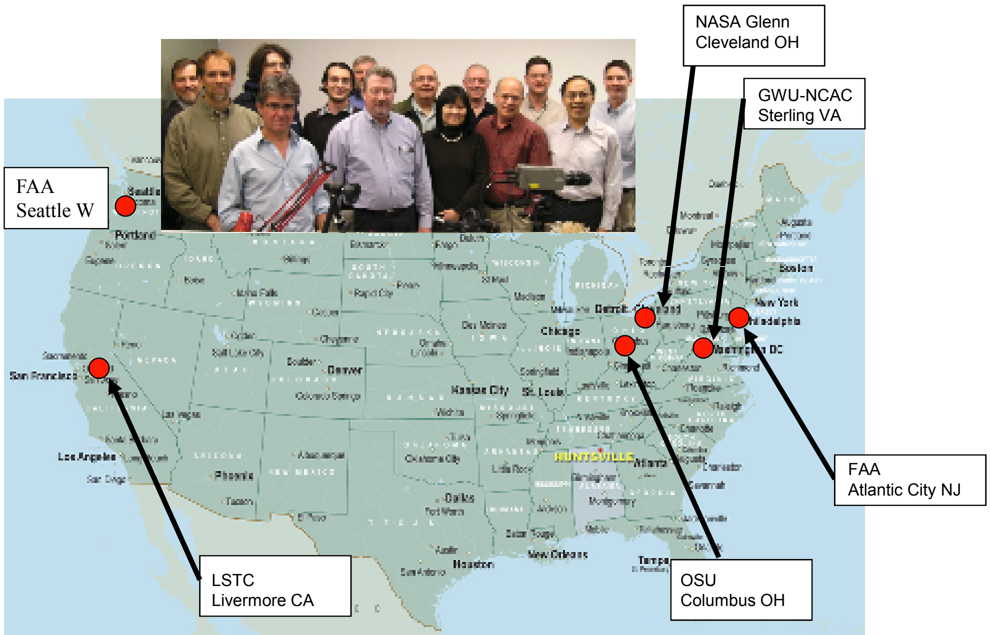
- **material testing performed by OSU**
- **ballistic testing performed by NASA/GRC**
- **numerical simulations performed by GWU-NCAC**

- **involved the implementation in LS-DYNA of a tabulated generalisation of the Johnson-Cook material law with regularisation to accommodate simulation of ductile materials**

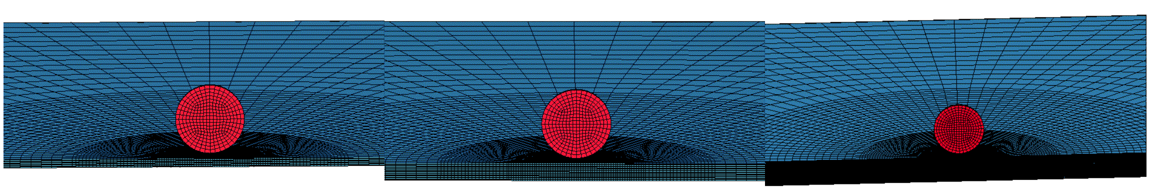
- **previously published results in :**

▪**A Generalized, Three Dimensional Definition, Description and Derived Limits of the Triaxial Failure of Metals, Carney, DuBois, Buyuk, Kan, Earth&Sky, march 2008**

FAA engine safety working group



penetration failure modes



1/16” – 1035.1 ft/s **1/8” – 1142 ft/s** **1/4” – 1875.4 ft/s**

Petaling → **Plugging**

Bending → **Shearing**
Necking **Spaling**

Part 1 :

OVERVIEW OF MAT_224

Development of MAT_224 in LS-DYNA

- **The Johnson-Cook material law is based on a multiplicative decomposition of strain hardening, strain rate hardening and thermal softening :**

$$\sigma_y = \left(a + b\varepsilon_p^n\right)\left(1 + c\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_R}{T_m - T_R}\right)^m\right)$$

- **A similar formulation is used for the plastic failure strain in function of state of stress (triaxiality), temperature and strain rate**

$$\varepsilon_{pf} = \left(D_1 + D_2 e^{D_3 \frac{p}{\sigma_{vm}}}\right)\left(1 + D_4 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 + D_5\left(\frac{T - T_R}{T_m - T_R}\right)\right)$$

- **A damage variable with scalar accumulation is used as failure criterion :**

$$d = \int \frac{d\varepsilon_p}{\varepsilon_{pf}} \leq 1$$

- **Exactly the same approach is followed in MAT_224**
- **analytical formulations are replaced by tabulated generalisation**

Development of MAT_224 in LS-DYNA

- regularisation of the displacement at failure is added to account for the inevitable mesh-dependency of the simulations after necking in ductile materials
- started development in november 2006
- production version available in ls971-R4.2
- current presentation is based on implementation in ls971-R5.0
- developed on the basis of MAT_024 with VP=1
- available for fully and underintegrated shell and solid elements
- full keyword code : *MAT_TABULATED_JOHNSON_COOK

MAT_224 : material law

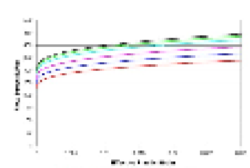
*MAT_TABULATED_THERMO_VISCOPLASTICITY_WITH_FAILURE

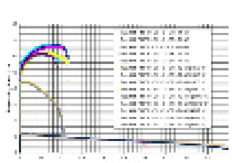
TITLE

1	MID	RO	E	PR	CP	TR	BETA
	4	2.7e-009	0.7466e + 005	0.3	8.75e + 006	300.0	1.0
2	k1	kt	f	g	h	i	
	11	12	15	16	17	18	0.0

k1 : table of rate dependent isothermal hardening curves or load curve defining quasistatic hardening curve

kt : table of temperature dependent quasistatic hardening curves



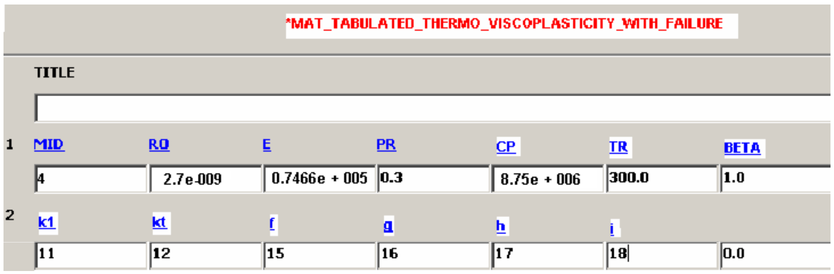


$$\sigma_y = k1(\varepsilon_p, \dot{\varepsilon}_p) \cdot kt(\varepsilon_p, T)$$

$$\varepsilon_p = \int \dot{\varepsilon}_p$$

$$T = T_R + \frac{\beta}{C_p \rho} \int \sigma_y \dot{\varepsilon}_p$$

MAT_224 : failure model



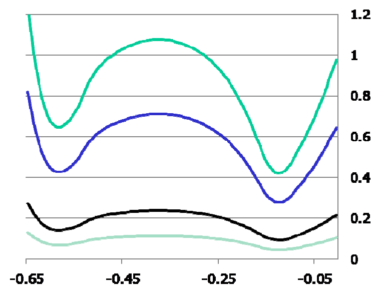
f : table of load curves giving failure plastic strain in function of triaxiality at constant Lode angle

g : scaling function for rate effects

h : scaling function for temperature

i : regularisation curve

$$\varepsilon_{pf} = f\left(\frac{p}{\sigma_{vm}}\right) g(\dot{\varepsilon}_p)\, h(T)\, i(l_c)$$



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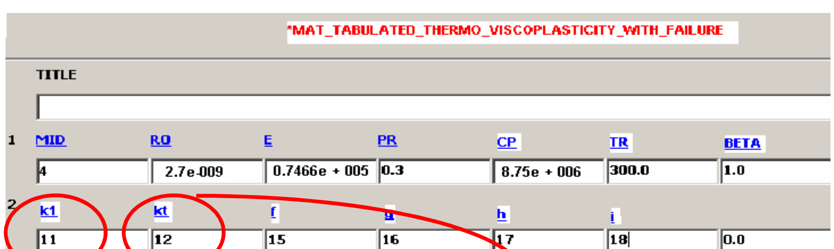
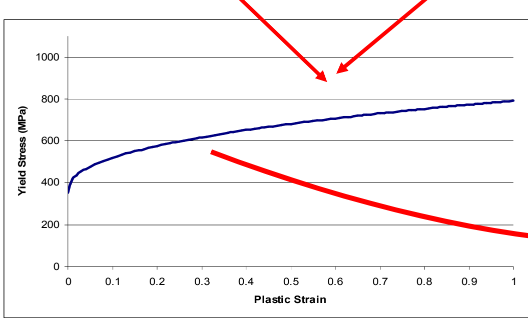
MAT_224 : material law : basic example



$$\sigma_y = k1(\varepsilon_p, \dot{\varepsilon}_p) \cdot kt(\varepsilon_p, T)$$

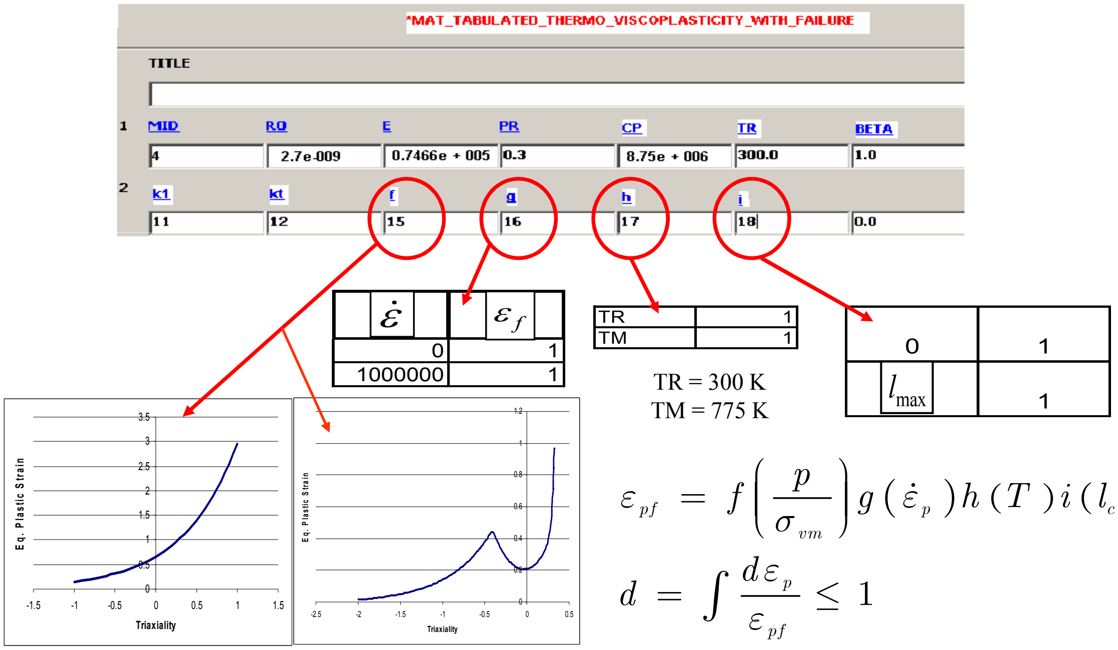


T	ε	σ
TR	$\sigma_y = k1(\varepsilon_p, \dot{\varepsilon}_p)$	
TM	0	

TR = 300 K

TM = 775 K

MAT_224 : failure law : basic example



$$\varepsilon_{pf} = f\left(\frac{p}{\sigma_{vm}}\right) g(\dot{\varepsilon}_p) h(T) i(l_c)$$

$$d = \int \frac{d\varepsilon_p}{\varepsilon_{pf}} \leq 1$$

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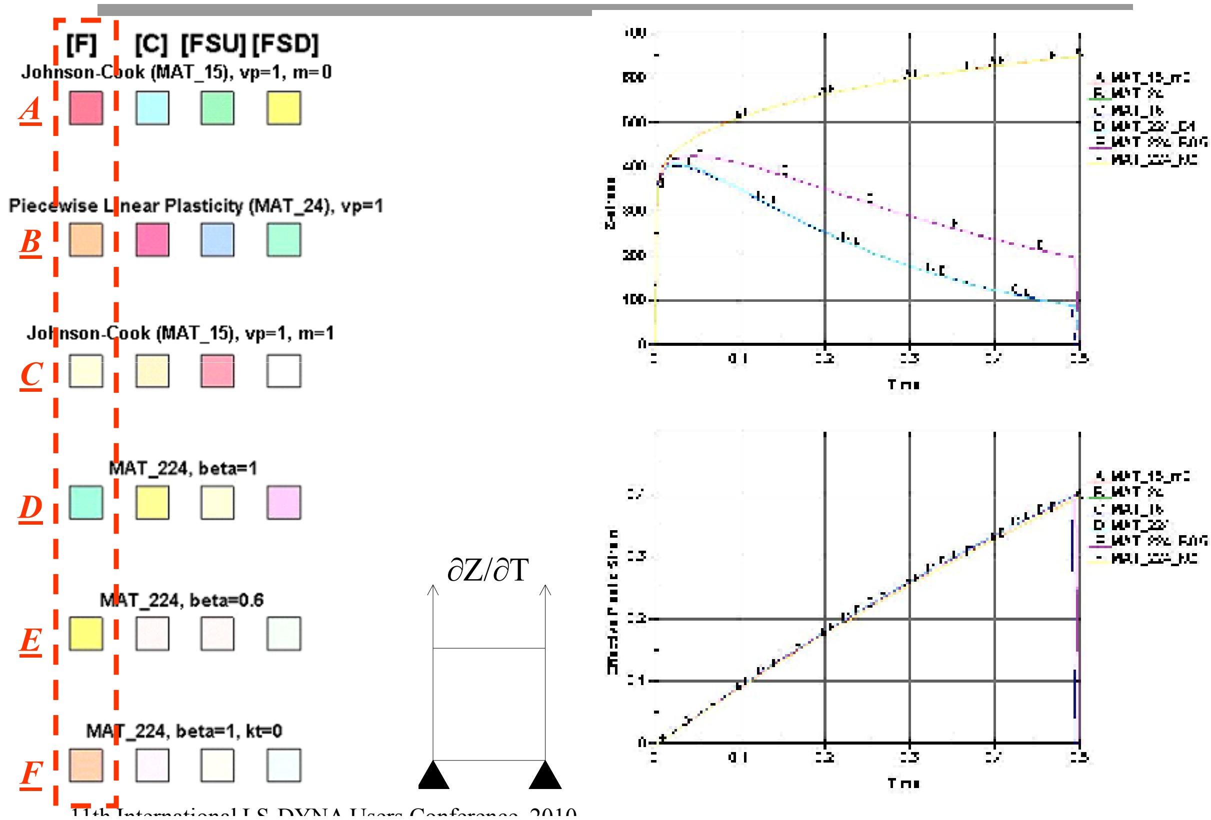
MAT_224 : Verification Process

- **extensive verification needs to be performed**
- **some elementary single solid element tests are shown next**
- **resuls must be compared to reliably implemented material laws in LS-DYNA : natural choices are MAT_024 and MAT_015**
- **in particular verify the influence of thermal softening and stress triaxiality**



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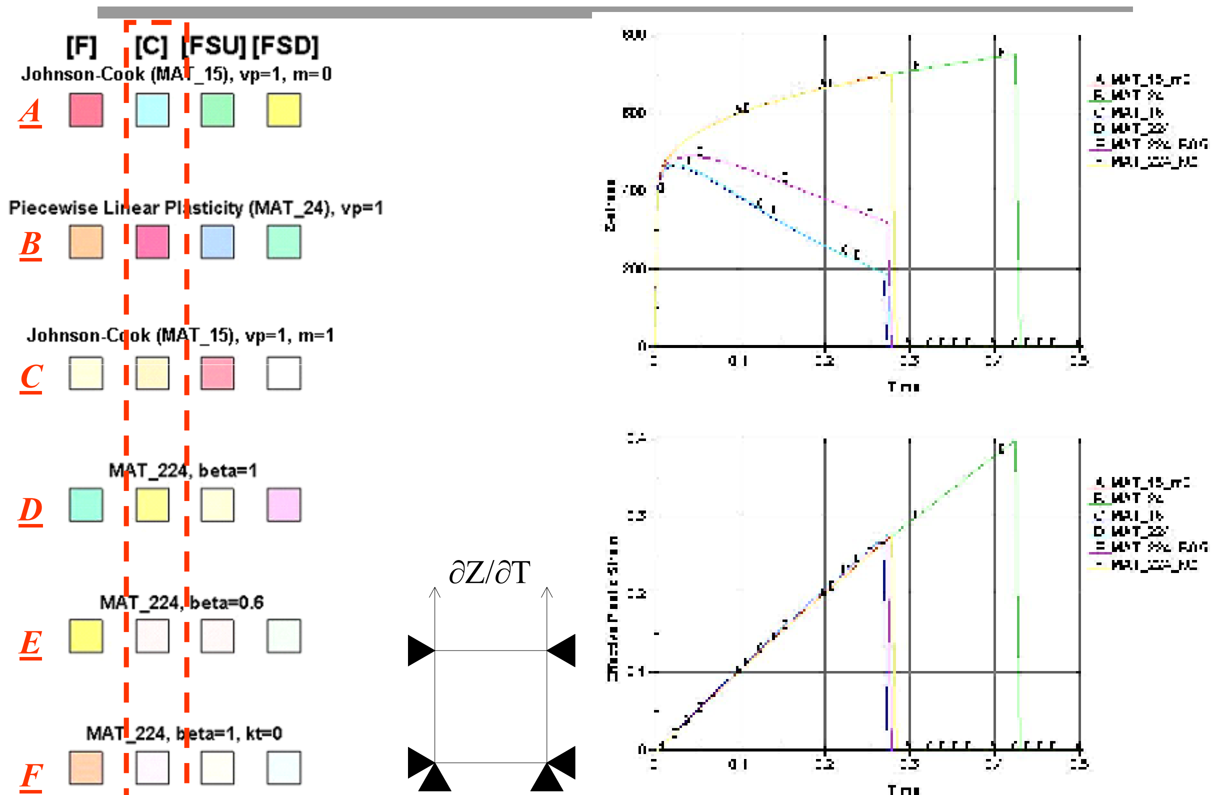

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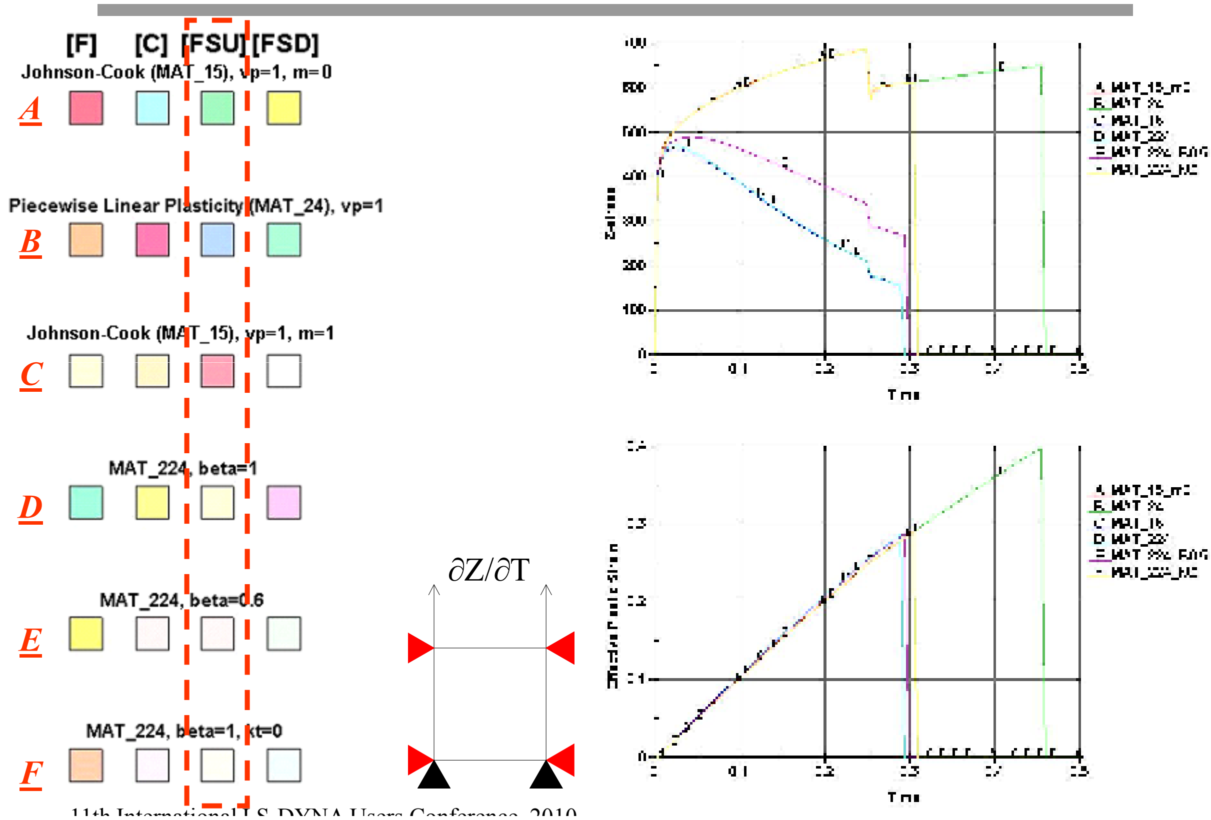

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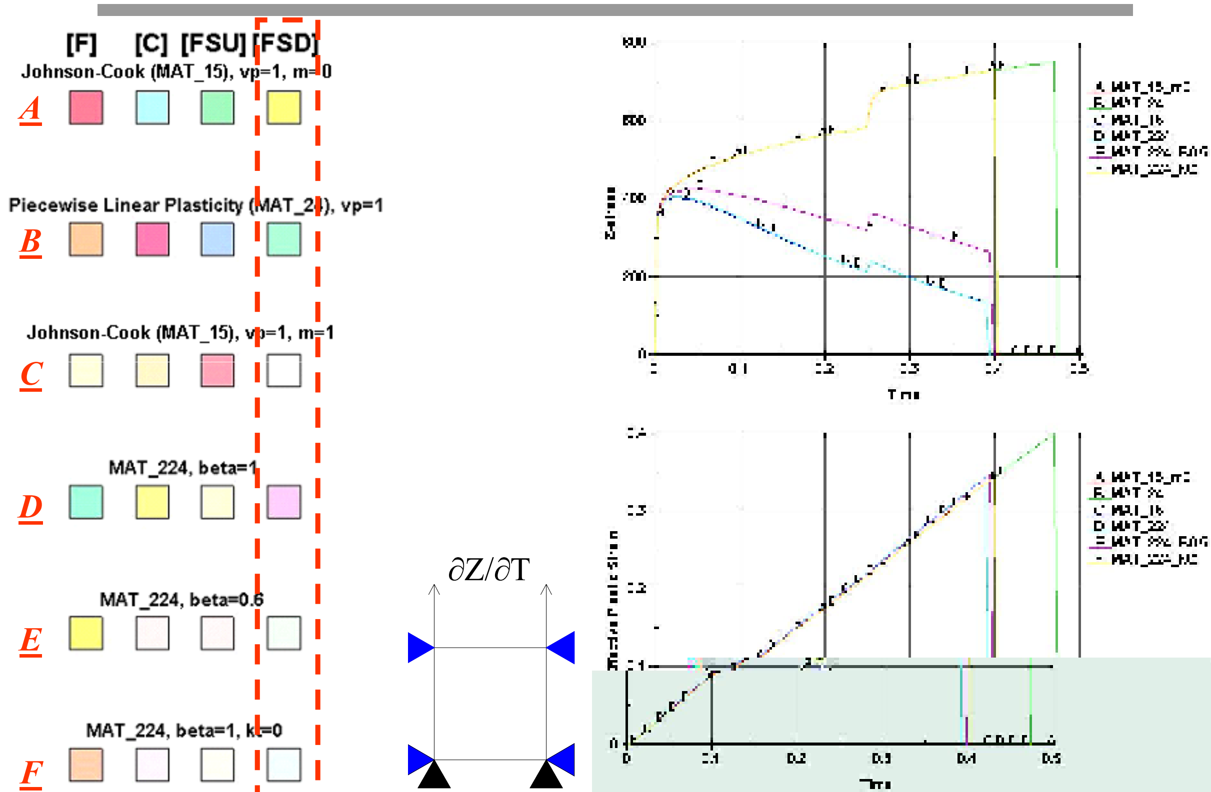

Once and for all : the history variables :

HV	Shell	Solid
1	Plastic strain rate	
5		Plastic strain rate
7	Plastic work	
8	Plastic strain/failure strain	Plastic failure strain
9	Element size	triaxiality
10	temperature	Lode angle
11	Plastic failure strain	Plastic work
12	Triaxiality	Plastic strain/failure strain
13		Element size
14		temperature

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Part 2 :

FAILURE MODEL DESCRIPTION
THE PLANE STRESS CASE

Characterisation of the state-of-stress

- **general state of stress :**

$$\begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \rightarrow \sigma_1 = 0 \Rightarrow \begin{cases} \sigma_2 < 0 \\ \sigma_3 < 0 \end{cases}$$

- **State-of-stress is compression only unless the first principal stress is strictly positive**

$$\sigma_1 > 0 \Rightarrow \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} = \sigma_1 \begin{pmatrix} 1 & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix}$$

- **2 parameters are needed to characterize the state-of-stress up to a multiplicative constant, one valid choice is :**

$$a = \frac{\sigma_2}{\sigma_1} \qquad b = \frac{\sigma_3}{\sigma_1}$$

Plane stress

- **general state of plane stress :**

$$\begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \rightarrow \begin{cases} \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & a\sigma_1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow 1 \geq a \geq 0 \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \Rightarrow \begin{cases} \sigma_2 \leq 0 \\ \sigma_3 \leq 0 \end{cases} \\ \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a\sigma_1 \end{pmatrix} \Rightarrow 0 \geq a \geq -\infty \end{cases}$$

- **invariants :**

$$p = -\frac{\sigma_1 + \sigma_2}{3}$$

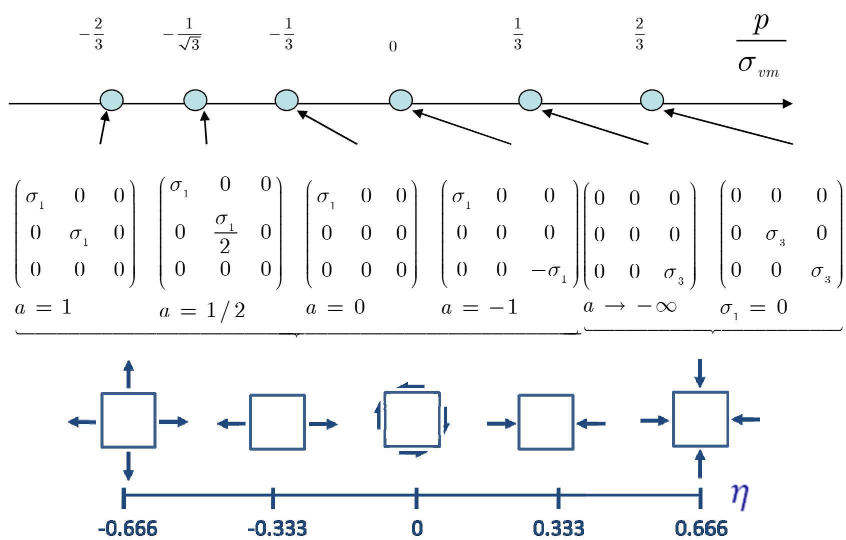
$$\sigma_{vm}^2 = \sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2$$

$$\frac{p}{\sigma_{vm}} = -\frac{1}{3}\frac{\sigma_1}{|\sigma_1|}\frac{1+a}{\sqrt{1+a^2-a}} = -\frac{1}{3}\frac{1+a}{\sqrt{1+a^2-a}}$$

$$\frac{p}{\sigma_{vm}} = -\frac{1}{3}\frac{\sigma_1}{|\sigma_1|}\frac{1+a}{\sqrt{1+a^2-a}} = -\frac{1}{3}\frac{1+a}{\sqrt{1+a^2-a}}$$

Important cases of plane stress

- **overview of plane states of stress :**



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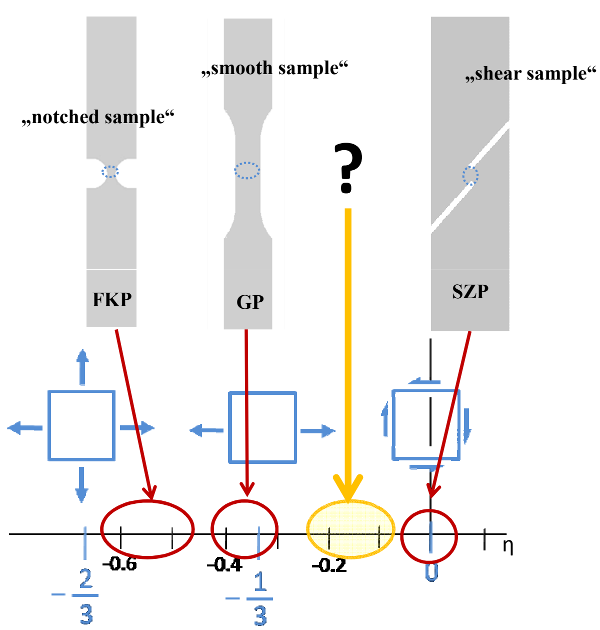
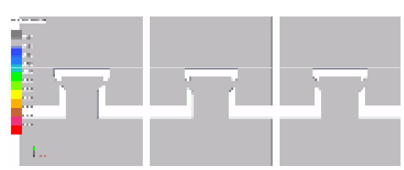
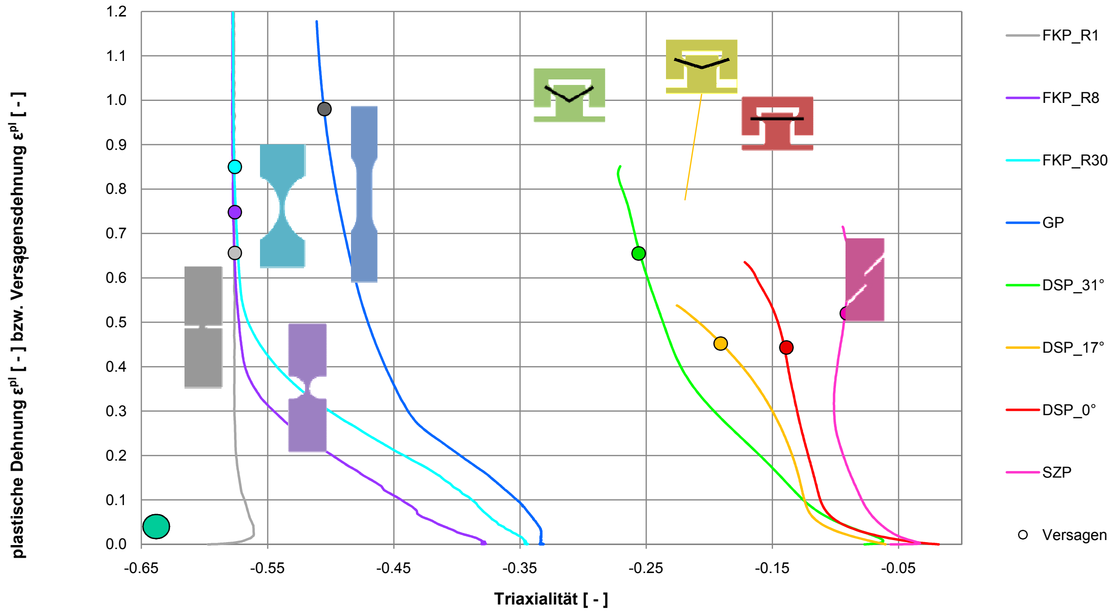
Example of a minimal test program for metal sheet :





Courtesy Adam Opel AG10

Failure model : step 1



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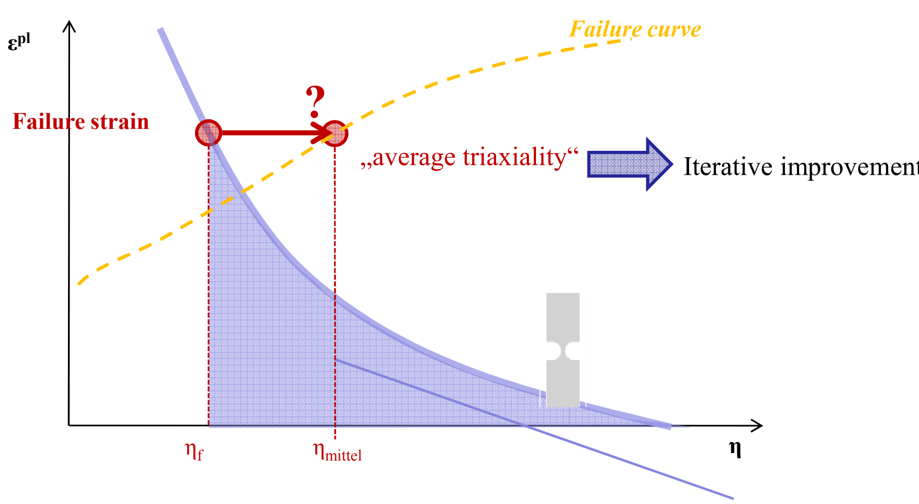
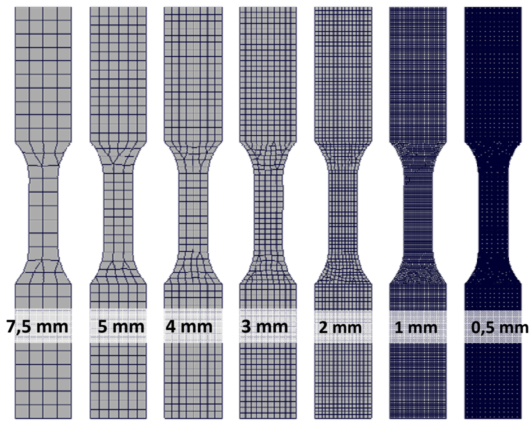
Failure model : step 2

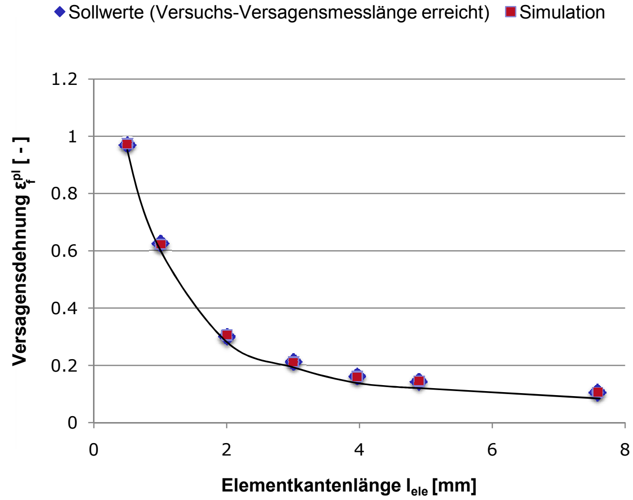


First estimate : $\eta_{mittel} = \frac{1}{\varepsilon_f^{pl}} \int_0^{\varepsilon^{pl}} \eta\,(\varepsilon) d\varepsilon$

Courtesy Adam Opel AG10

Failure model : step 3 : regularisation





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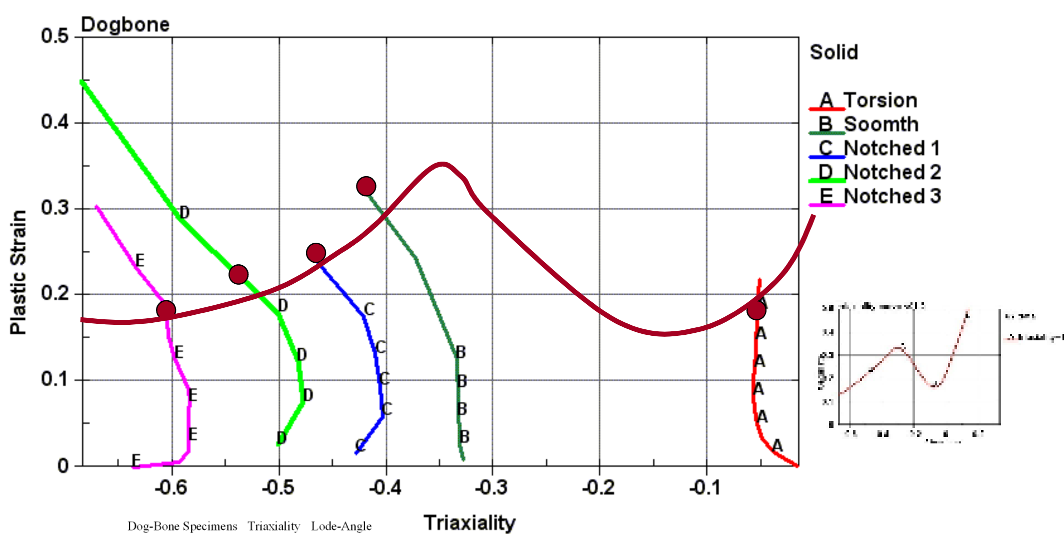
Plane stress Failure criterion for Aluminium 2024

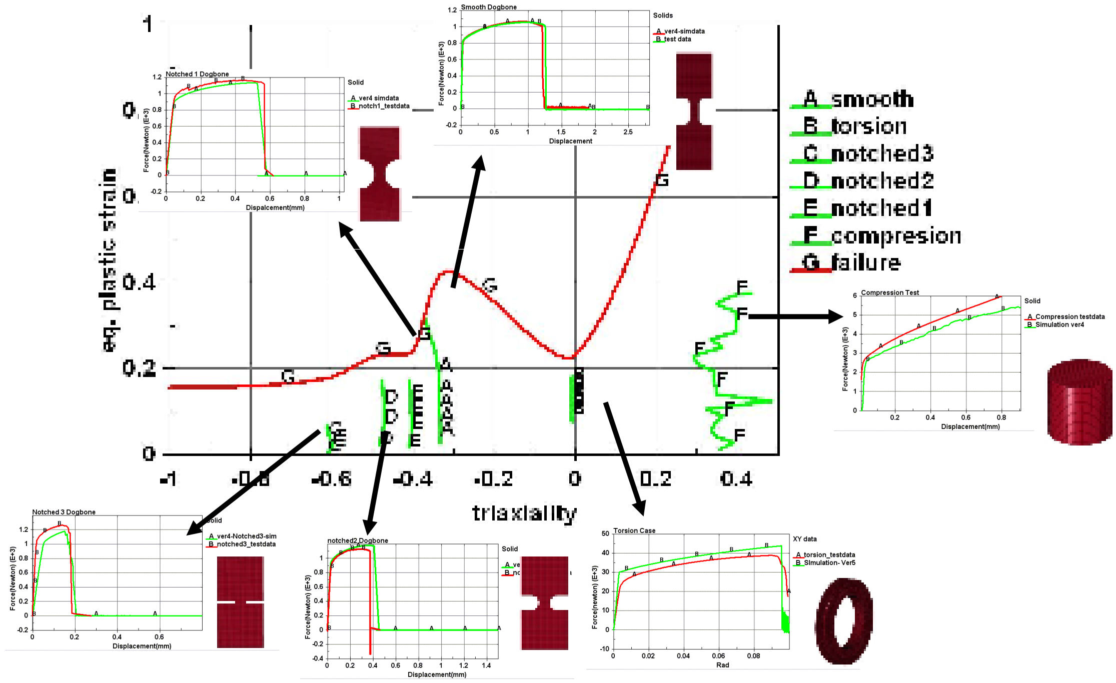


Dog-Bone Specimens	Triaxiality	Lode-Angle
1	-0.333	1
2	-0.41	0.915
3	-0.49	0.617
4	-0.577	0

Combined Loading	Triaxiality	Lode-Angle
1	-0.2505	0.915
2	-0.1466	0.617

Shear	Triaxiality	Lode-Angle
1	0	0

Plane stress Failure criterion for Aluminium 2024



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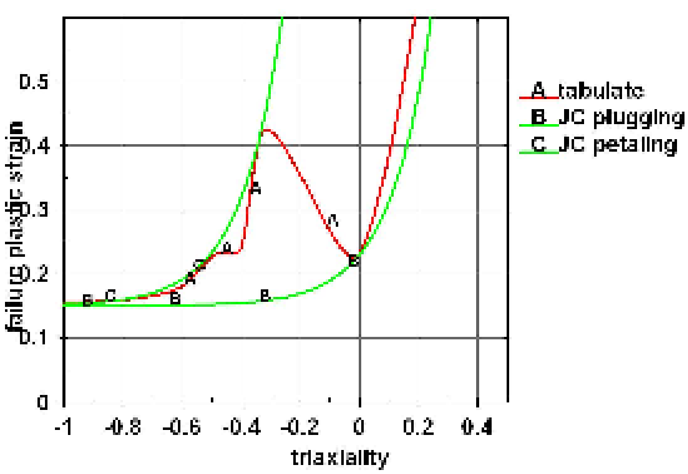
Comparison to JC failure criteria



In fact the JC criterion usually cannot handle petaling (tensile) and plugging (shear) failure simultaneously

Example of AL2024, the physical failure criterion is more complex then JC

Part 2 :

FAILURE MODEL DESCRIPTION THE 3D CASE

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dependency upon the state of stress : 3D case

- **in a 3D state of stress (solid elements) it cannot be assumed that the third invariant of the stress tensor is zero, 2 invariant parameters are needed to characterize the state of stress :**

$$\frac{p}{\sigma_{vm}} = -\frac{1}{3}\frac{\sigma_1}{|\sigma_1|}\frac{1+a+b}{\sqrt{1+a^2+b^2-ab-a-b}}$$

$$\frac{I_3}{\sigma_{vm}^3} = \frac{\sigma_1\sigma_2\sigma_3}{\sigma_{vm}^3} = \frac{\sigma_1^3}{|\sigma_1^3|}\frac{ab}{(1+a^2+b^2-ab-a-b)^{3/2}}$$

- **Lode angle is often used since it varies between -1 and 1**

$$\frac{J_3}{\sigma_{vm}^3} = \frac{I_3}{\sigma_{vm}^3} + \frac{p^3}{\sigma_{vm}^3} - \frac{p}{3\sigma_{vm}}$$

$$-1 \leq \frac{27J_3}{2\sigma_{vm}^3} = \frac{27s_1s_2s_3}{2\sigma_{vm}^3} \leq 1$$

material tests for failure criterion

Dog-Bone Specimens	Triaxiality	Lode-Angle
1	-0.333	1
2	-0.41	0.915
3	-0.49	0.617
4	-0.577	0

Axi-Symmetric Specimens	Triaxiality	Lode-Angle
1	-0.333	1
2	-0.41	1
3	-0.49	1
4	-0.577	1
5	-0.666	1
6	-0.8	1

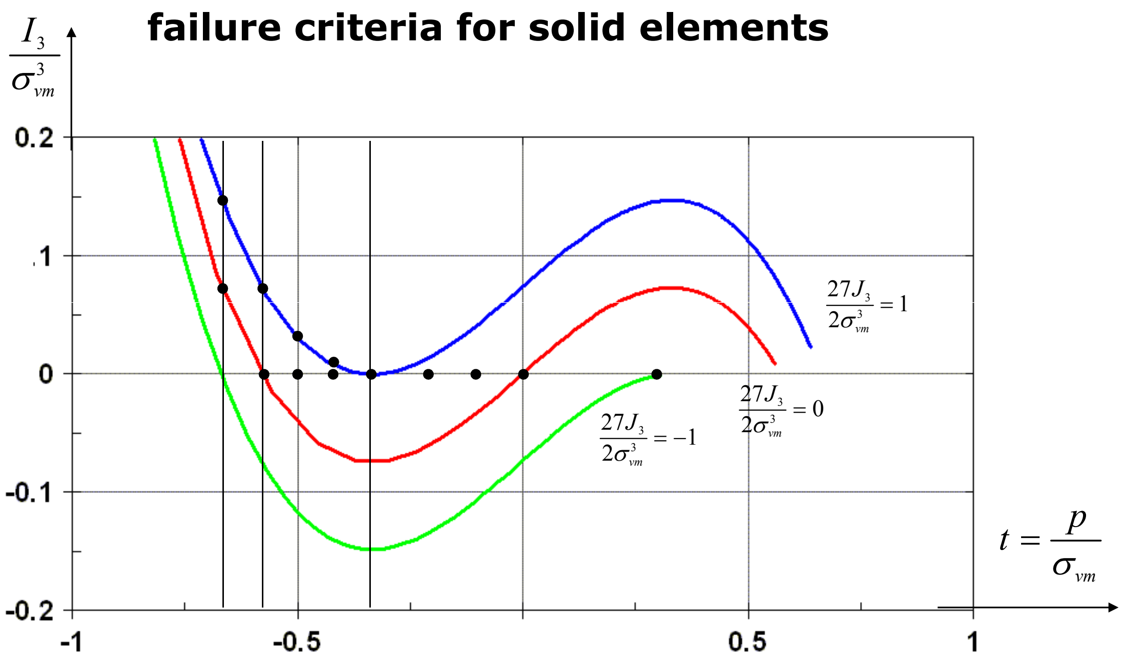
Compression Cylinders	Triaxiality	Lode-Angle
1 D20xL25, 2 D20xL20, 3 D20xL15, 4 D12xL12	0.333	-1

Grooved Plates	Triaxiality	Lode-Angle
1	-0.577	0
2	-0.666	0
3	-0.8	0

Shear	Triaxiality	Lode-Angle
1	0	0

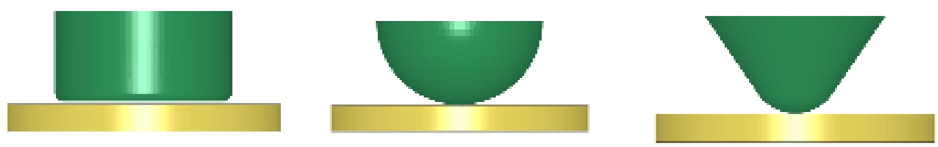
Combined Loading	Triaxiality	Lode-Angle
1	-0.2505	0.915
2	-0.1466	0.617

failure criteria for solid elements

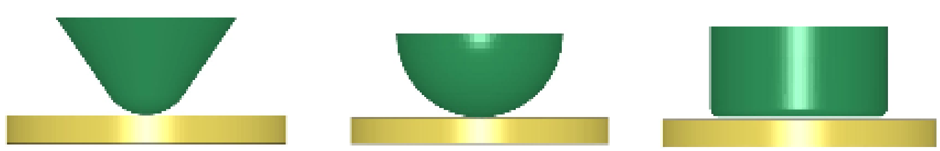


Dynamic punch testing on the SHB

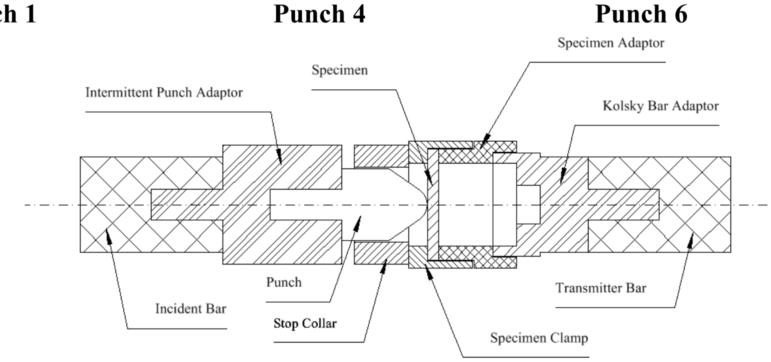
- Controlled dynamic testing is performed on a SHB to examine failure of Aluminium 2024 before assessing the ballistic testing by NASA
- SHB at OSU is used for dynamic punch testing at 20 m/s using different punch shapes and a circular sample with D=14.56 mm and t=1.456 mm (10%)
- 3 different punch shapes were selected
- these tests allow validation of the failure criteria determined from quasistatic testing on samples with different shapes
- also failure criterion can be extended to states of stress lying on the compressive meridian
- crack patterns corresponding to different failure modes (petaling, plugging and combined) can be examined
- stop collars were used to arrest the impactor bar at predetermined values of the displacement allowing to study the crack growth in the samples



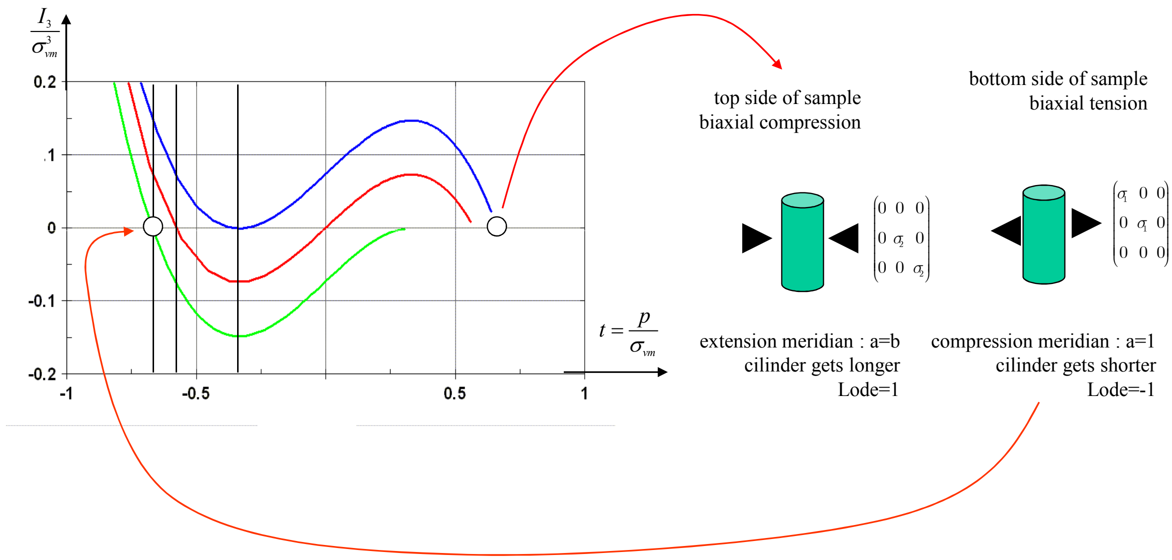
dynamic punch testing on the SHB



Punch 1 **Punch 4** **Punch 6**



what happens during a punch test ?

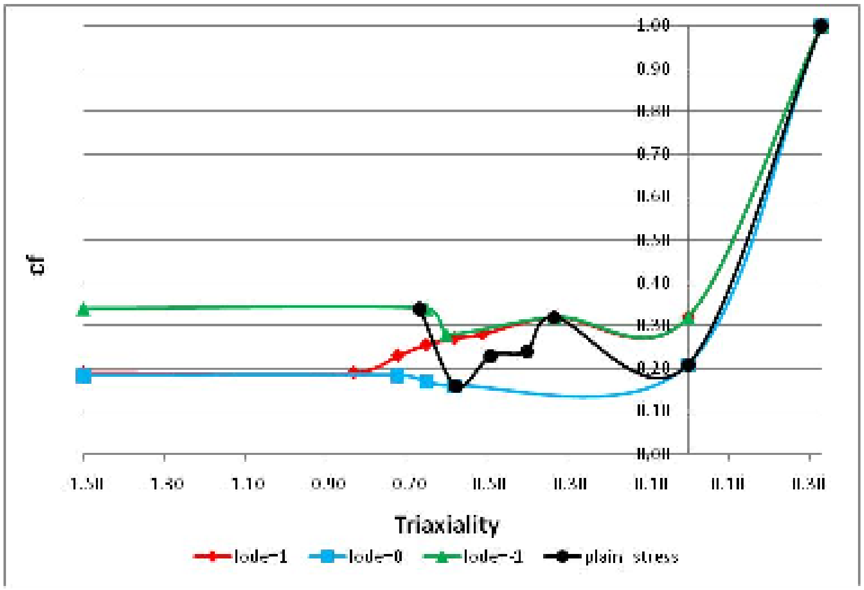


~Lode	1	0.915	0.617	0	-1
~Triaxiality					
-0.8	Cylinder G6			Grooved Plate G3	
-0.666	Cylinder G5			Grooved Plate G2	Punch 1
-0.577	Cylinder G4			Dogbone G4 Grooved Plate G1	Punch 4
0.49	Cylinder G3		Dogbone G3		
-0.41	Cylinder G2	Dogbone G2			
-0.333	Cylinder G1 Dogbone G1				
-0.2505		Tension/Torsion			
-0.1466			Tension/Torsion		
0				Torsion Punch 6	
0.333					Compression

Spline-1 Free Points Spline-2 Spline-3

Spline-4

Basic splines for the 3D failure model



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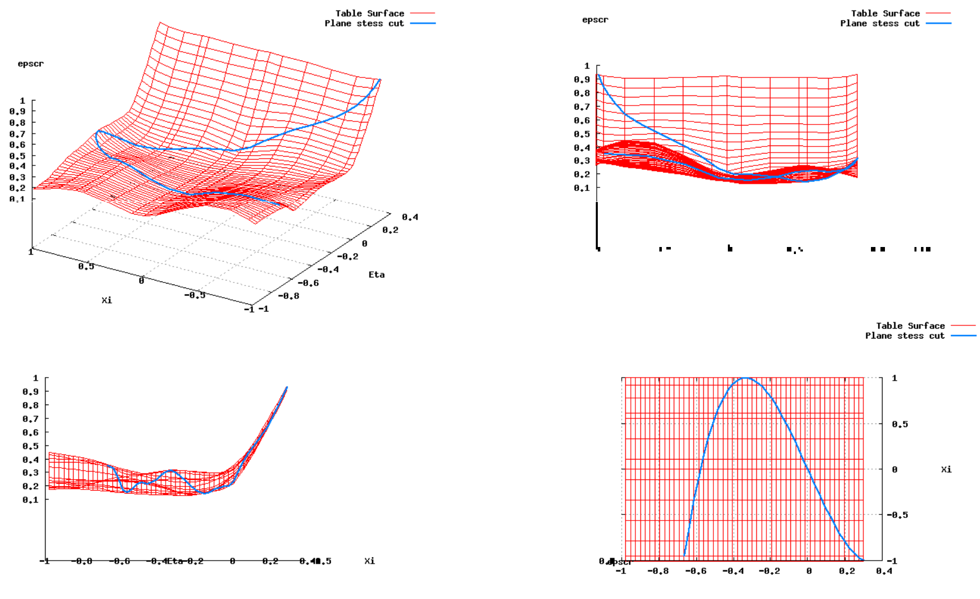
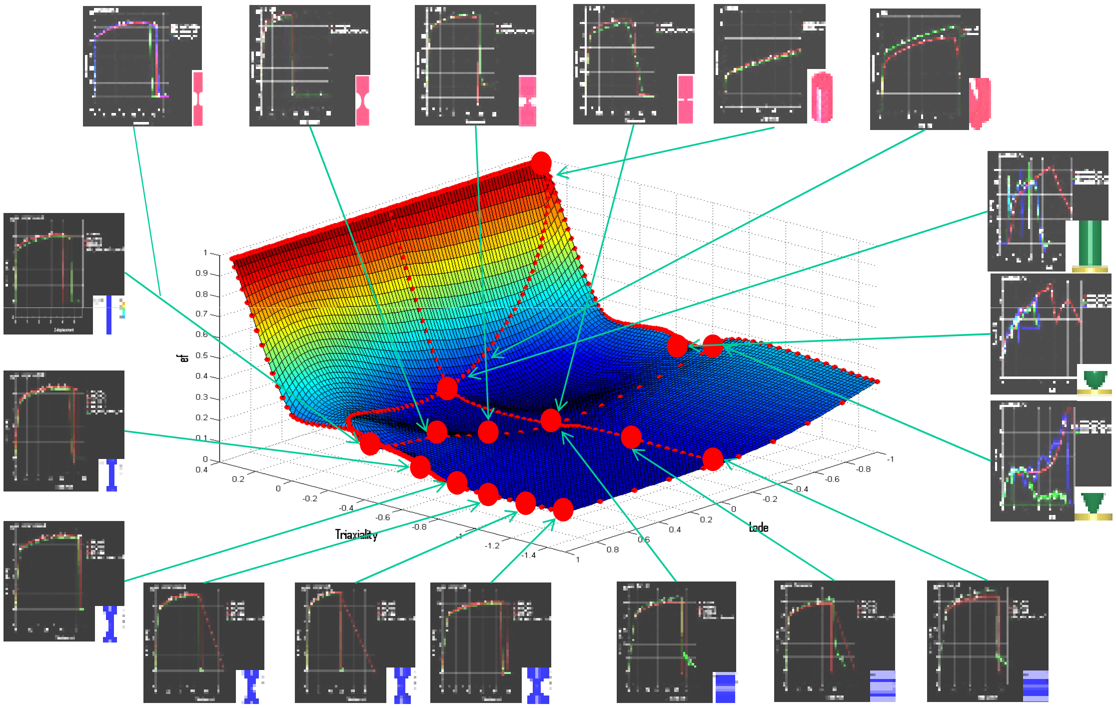
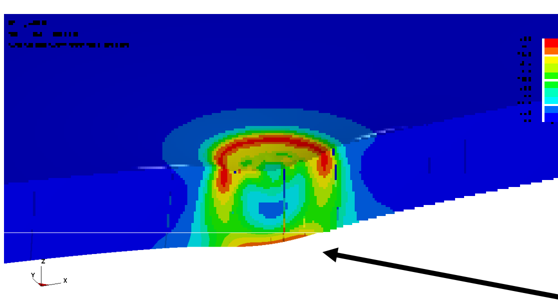
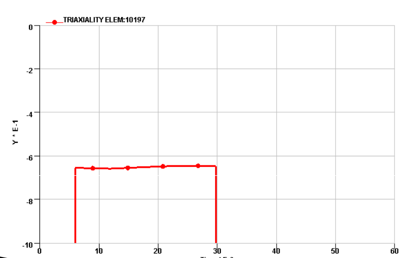
3-D Failure criterion for Aluminium 2024

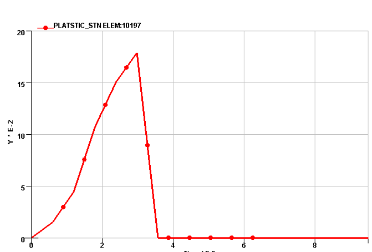


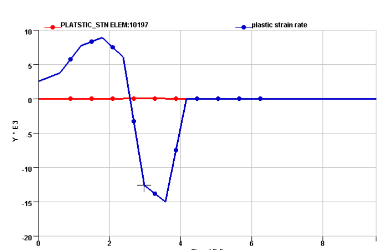


preliminary simulation results : punch 1

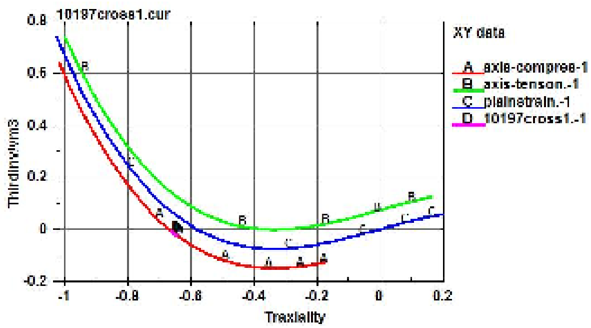


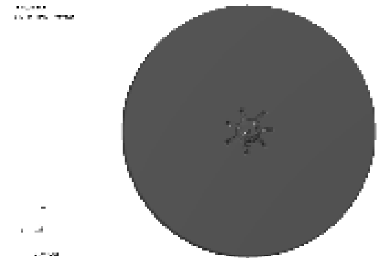




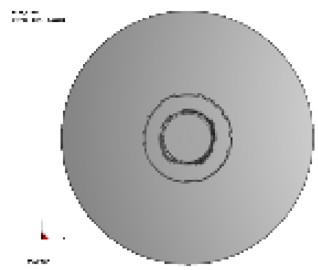


preliminary simulation results : punch 1



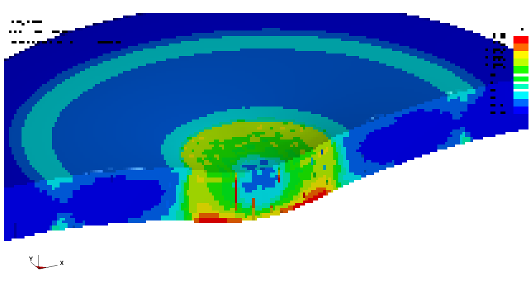


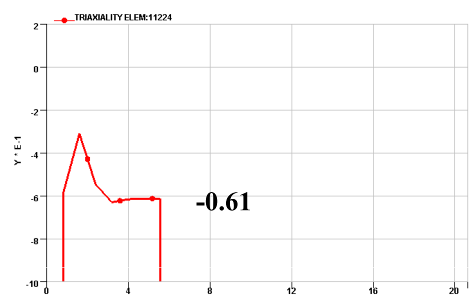
bottom view

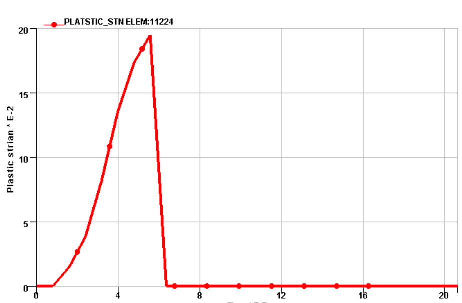


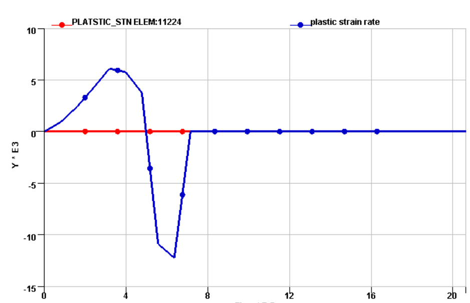
top view

preliminary simulation results : punch 4

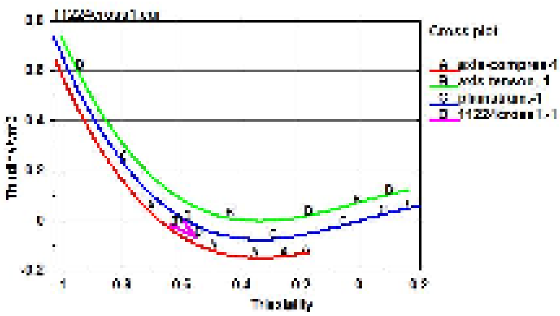


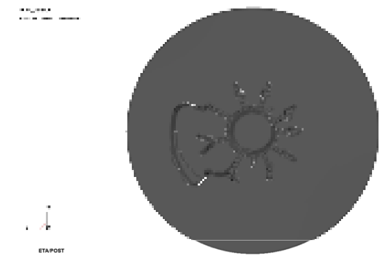


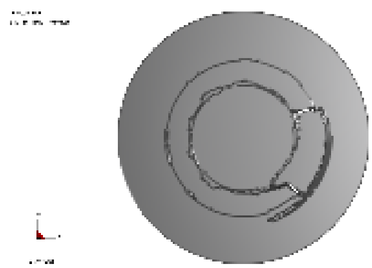




preliminary simulation results : punch 4

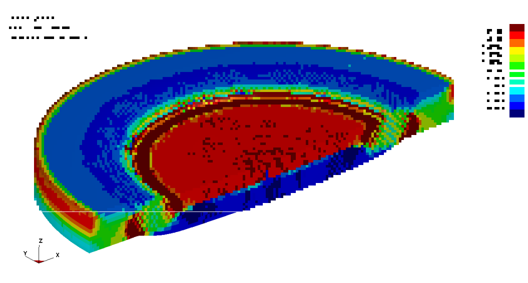


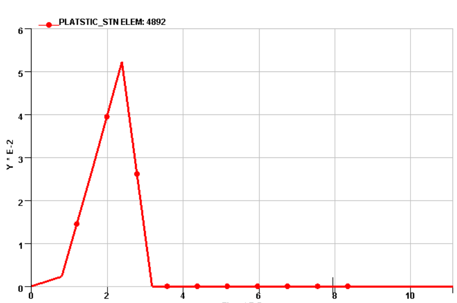


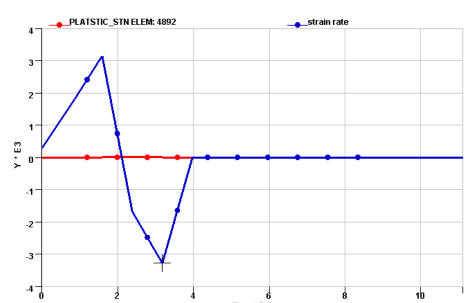


Development, Implementation and Validation of 3-D Failure Model for Aluminium 2024

preliminary simulation results : punch 6







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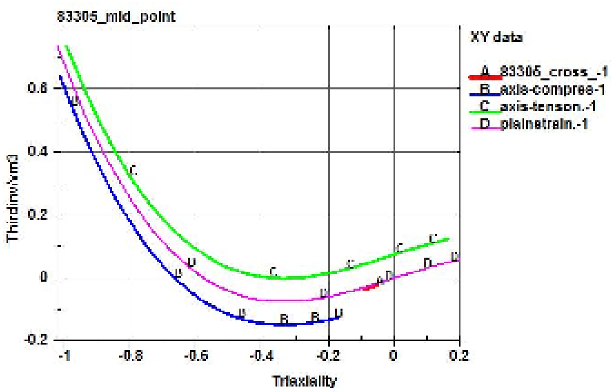
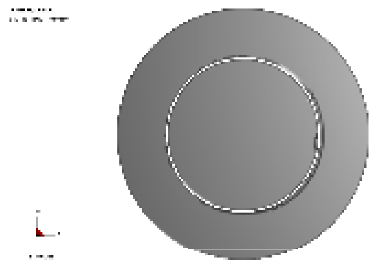
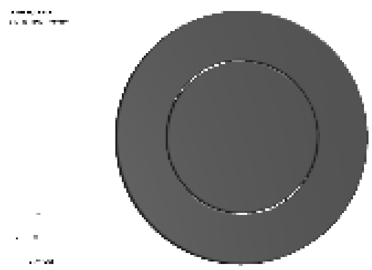
preliminary simulation results : punch 6



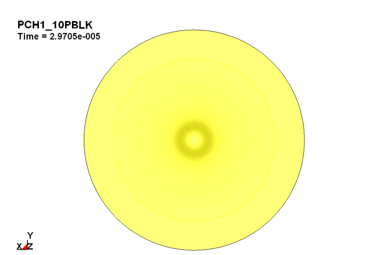


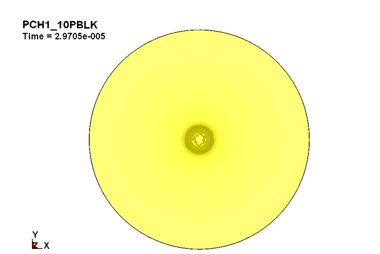


Development, Implementation and Validation of 3-D Failure Model for Aluminium 2024

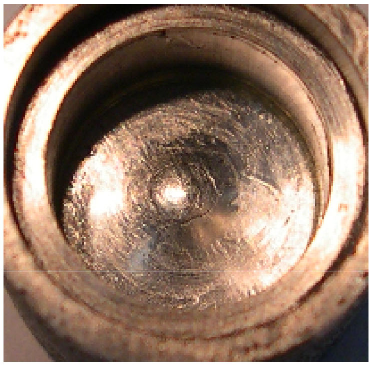
Comparison to SHB test results : 1mm displacement

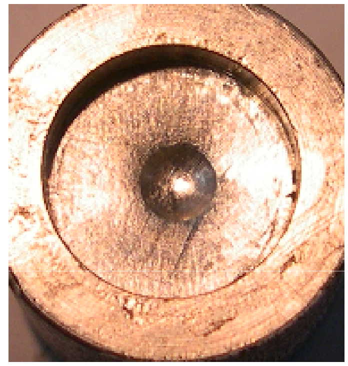
bottom no cracks yet top



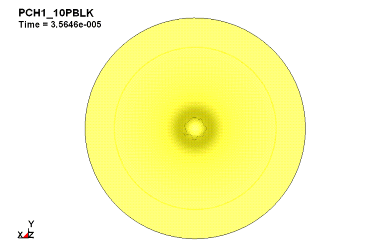


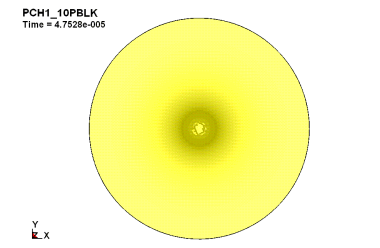
Comparison to SHB test results : 1.7mm displacement





circumferential crack at bottom side

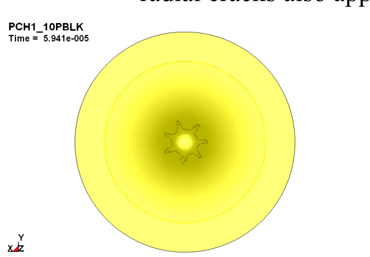


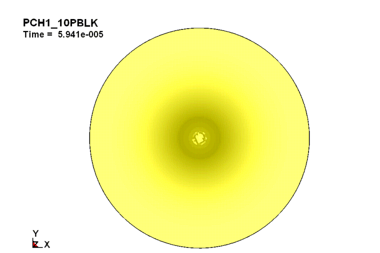


Development, Implementation and Validation of 3-D Failure Model for Aluminium 2024

Comparison to SHB test results : 2.4mm displacement

radial cracks also appear at the bottom side





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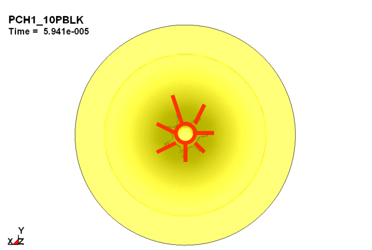
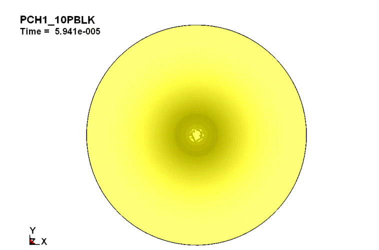
animated simulation results

Development, Implementation and Validation of 3-D Failure Model for Aluminium 2024

Comparison to SHB test results : 2.4mm displacement

radial cracks also appear at the bottom side





Part 3 :

CONCLUSION

Development, Implementation and Validation of 3-D Failure Model for Aluminium 2024

Continuation

- **further iterations using the material and punch test results to refine the failure model**
- **simulation of the ballistic tests performed at GRC to assess the current model**

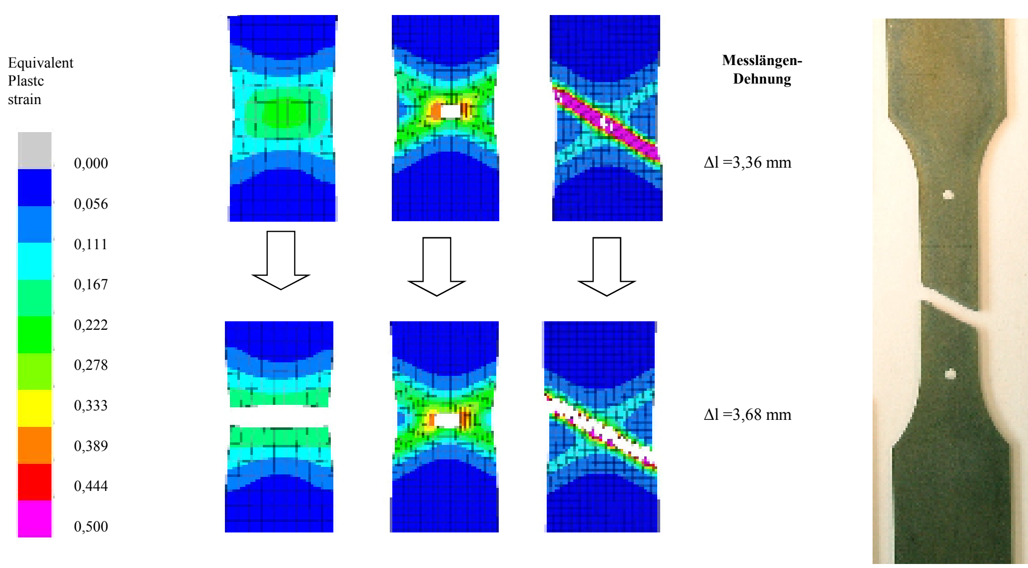
Limitations of the current method

- material may not yield according to the von Mises yield surface :

$$\sigma_c > \sigma_t \qquad \sigma_s < \frac{\sigma_t}{\sqrt{3}}$$

- material may be anisotropic
- damage accumulation may need to be tensorial if cyclic loading is considered
- regularisation may not be uncoupled from the state of stress, the current approach will fail to correctly simulate failure induced by plastic instability
- some of these considerations will need to be assessed when titanium is investigated next

Mesh dependent orientation of the localized neck



Conclusions

- predictive analysis of failure is desribale for materials used in aeronautical structures
- to achieve maximum flexibility in the numerical models a tabulated and regularized generalisation of the Johnson-Cook material law was implemented in LS-DYNA
- a comprehensive testing program was used to create a material data card for aluminium 2024
- it proved possible to predict the complicate crack pattern in a dynamic punch test
- the results of the punch tests can be used for further fine tuning of the material dataset