TMF and deviating crystal orientation in single-crystal superalloys

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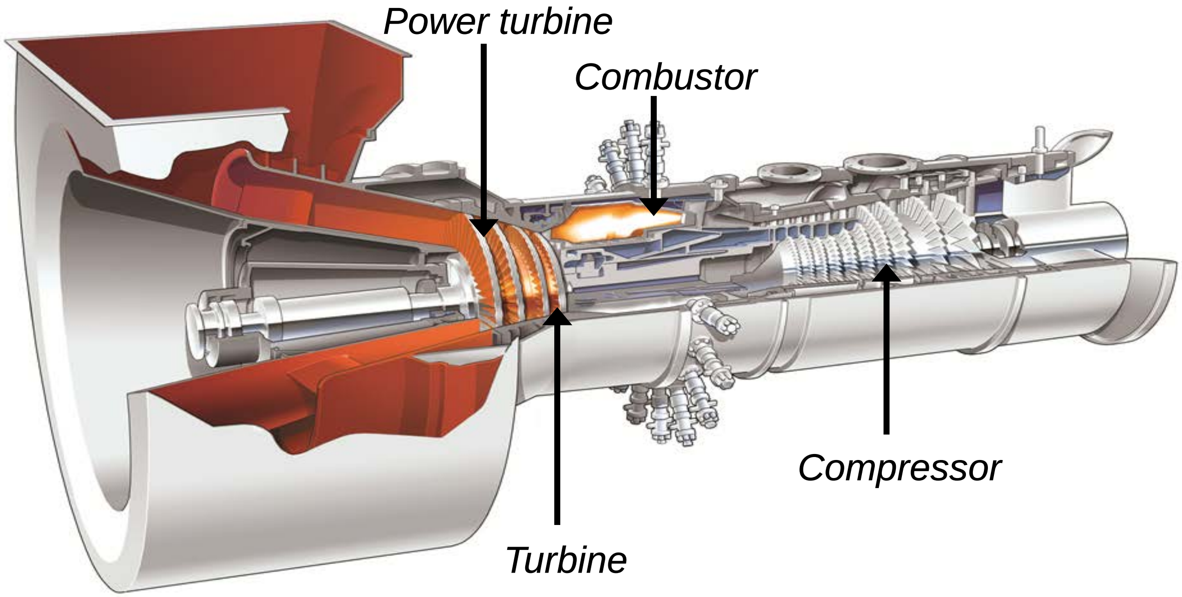
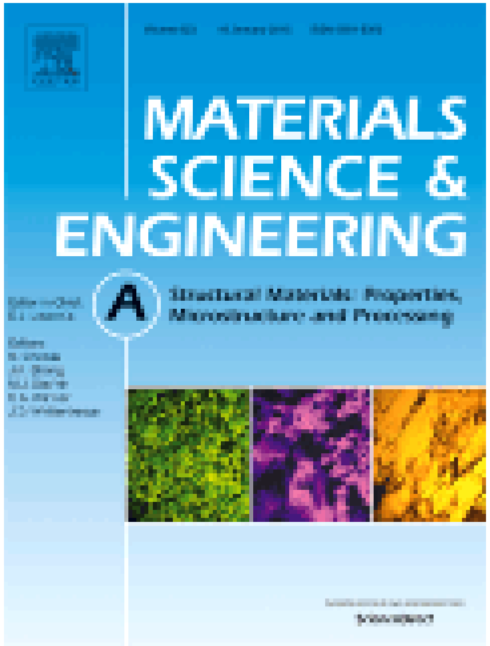
LiU EXPANDING REALITY

Overview

- TMF life contra orientation misalignment
- TMF crack initiation paper



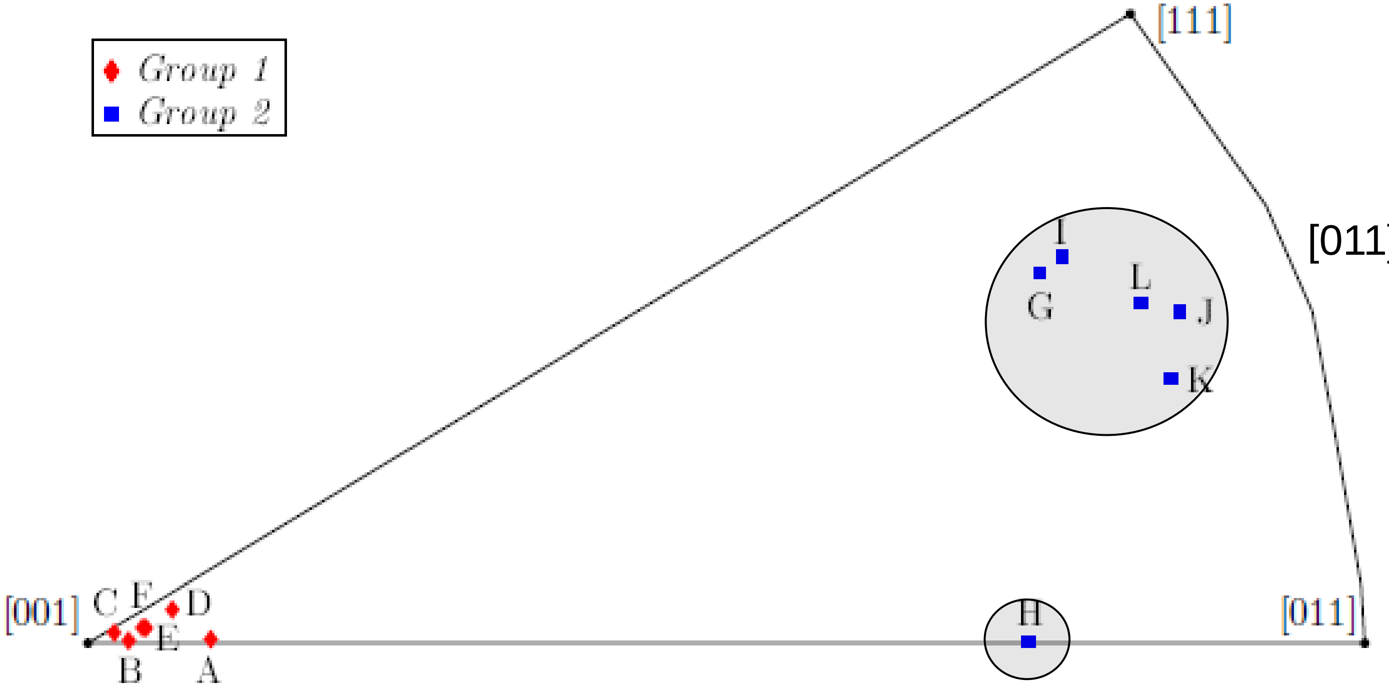
Misaligned paper



- *Influence of crystal orientation on the thermomechanical fatigue behaviour in a single-crystal superalloy*
- M. Segersäll, D. Leidermark & J.J. Moverare
- Materials Science & Engineering A, Vol 623, (2015), pp. 68-77.

Misalignment

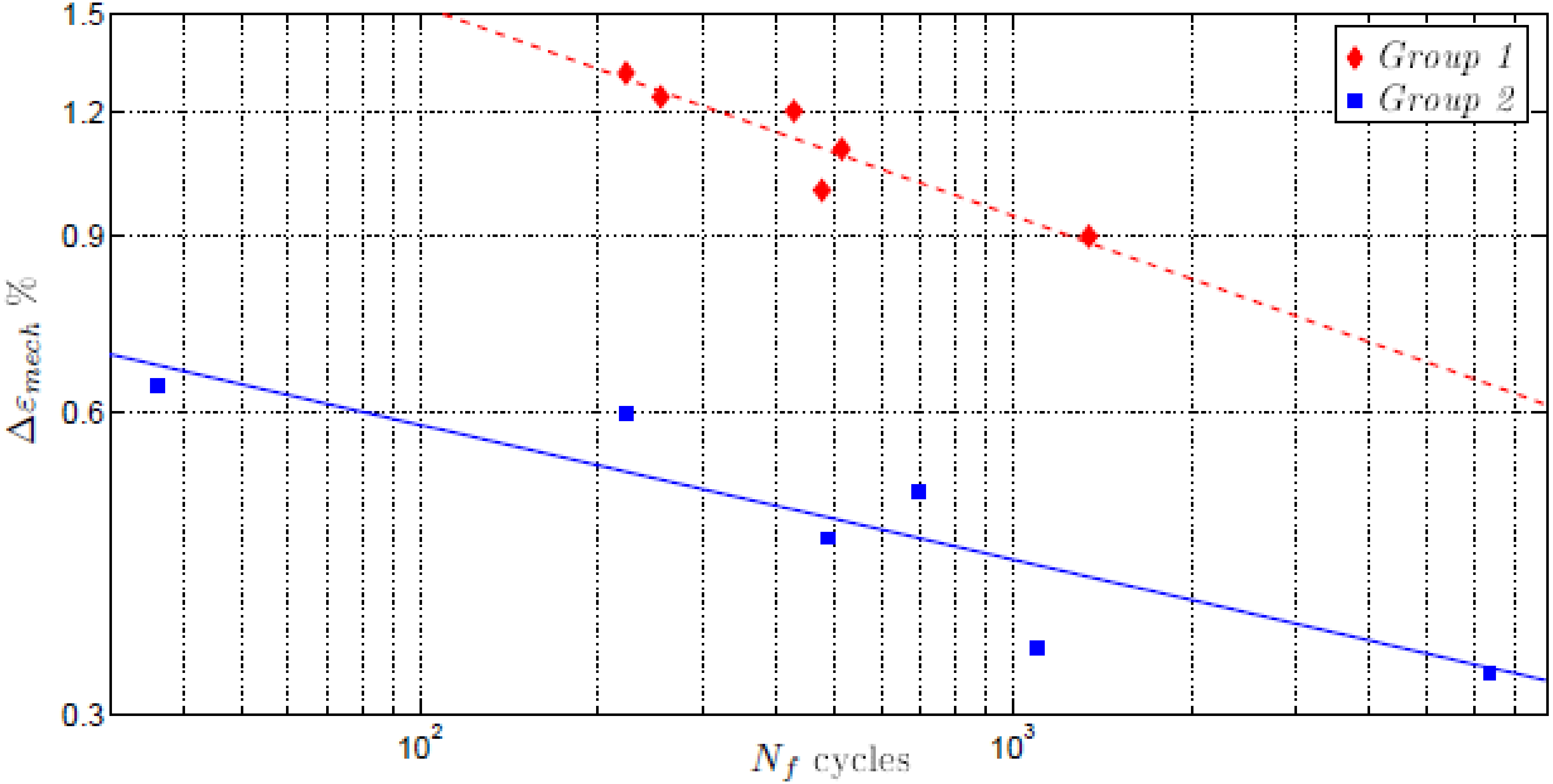
- Orientation misalignments from manufacturer
- Stereographic triangle



[011] orientations?

TMF experimental lives

- Scatter in OP TMF life.



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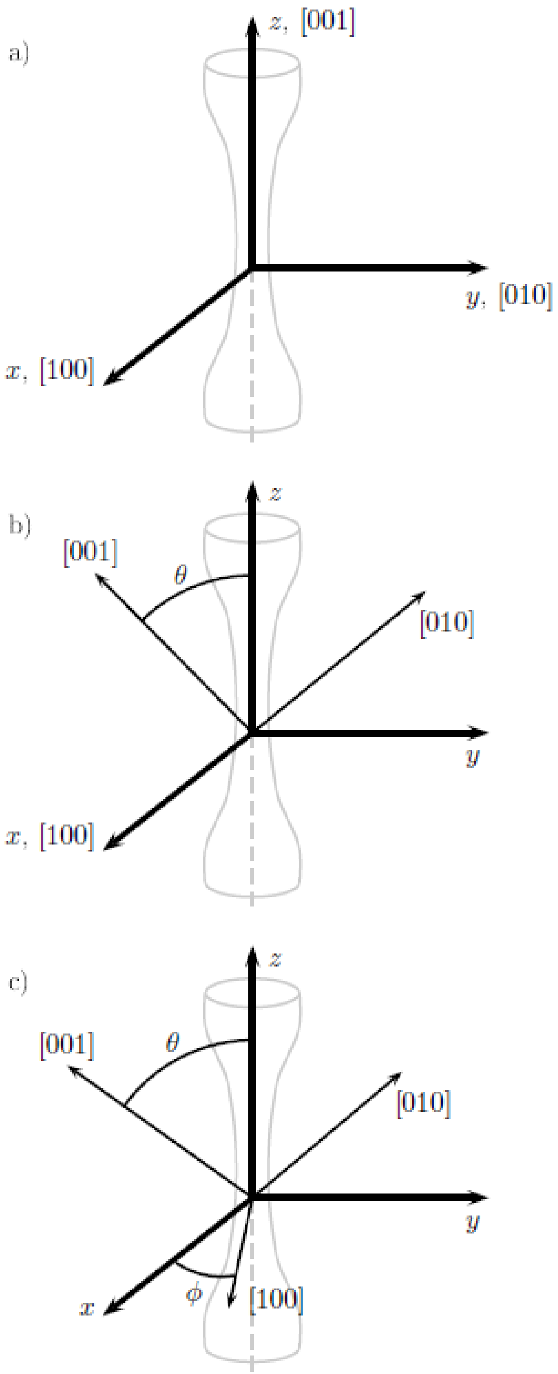


Crystal orientation

- Two angles define specimen crystal orientation.
- Loading in z-direction, from perfect [001]
- $$\boldsymbol{X} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
- $\boldsymbol{A} = \boldsymbol{Q}_2\boldsymbol{Q}_1\boldsymbol{X}$ described in global FE-coordinates

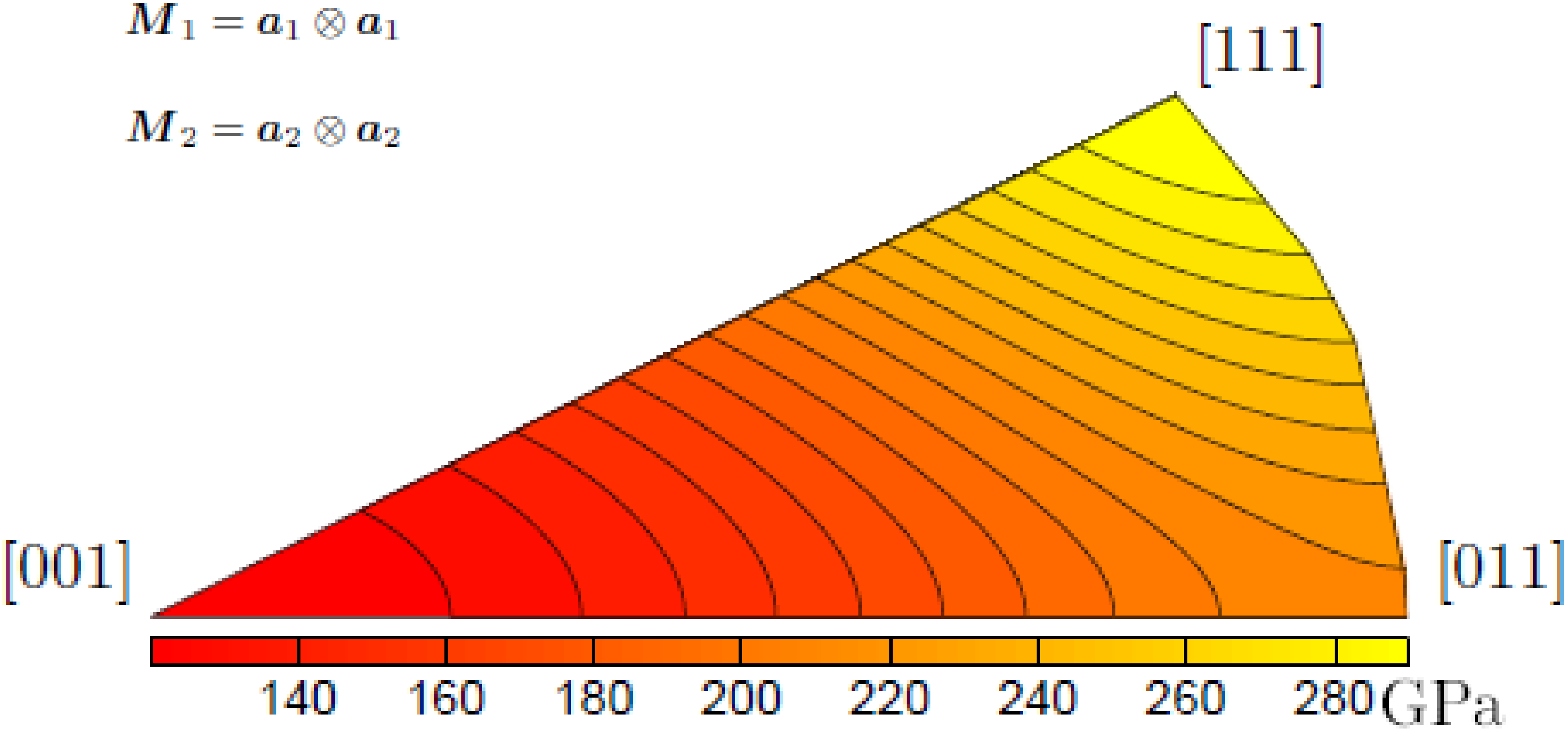
Uniaxial numerical stiffness

$$\mathbb{C}^e = \lambda \boldsymbol{I} \otimes \boldsymbol{I} + \mu(\boldsymbol{I} \underline{\otimes} \boldsymbol{I} + \boldsymbol{I} \overline{\otimes} \boldsymbol{I}) + 2\eta(\boldsymbol{M}_1 \otimes \boldsymbol{M}_1 + \boldsymbol{M}_2 \otimes \boldsymbol{M}_2$$

$$+ \boldsymbol{M}_1 \otimes \boldsymbol{M}_2 - \boldsymbol{I} \otimes \boldsymbol{M}_1 - \boldsymbol{I} \otimes \boldsymbol{M}_2)_{ms}$$

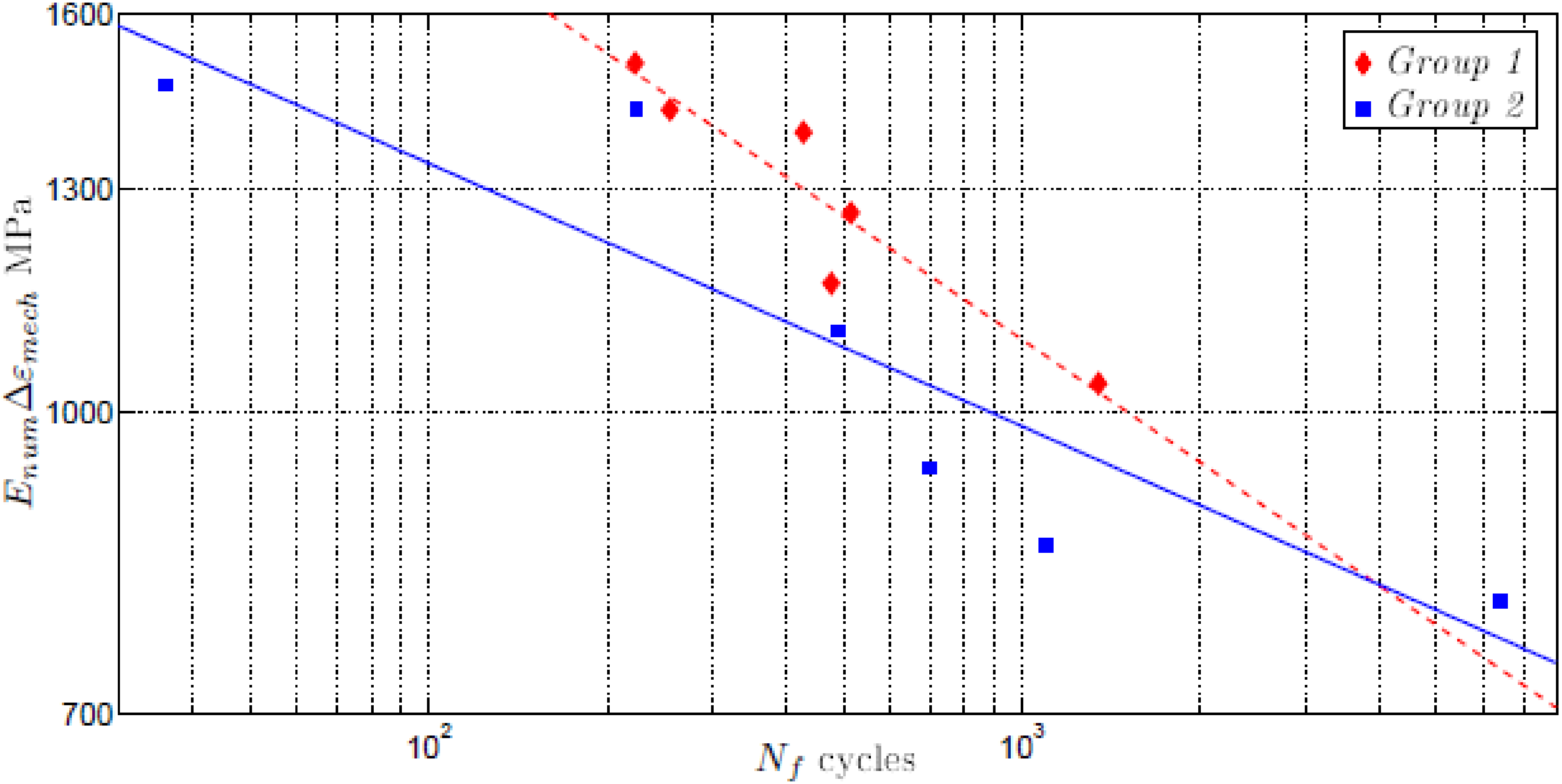
$$\boldsymbol{M}_1 = \boldsymbol{a}_1 \otimes \boldsymbol{a}_1$$

$$\boldsymbol{M}_2 = \boldsymbol{a}_2 \otimes \boldsymbol{a}_2$$

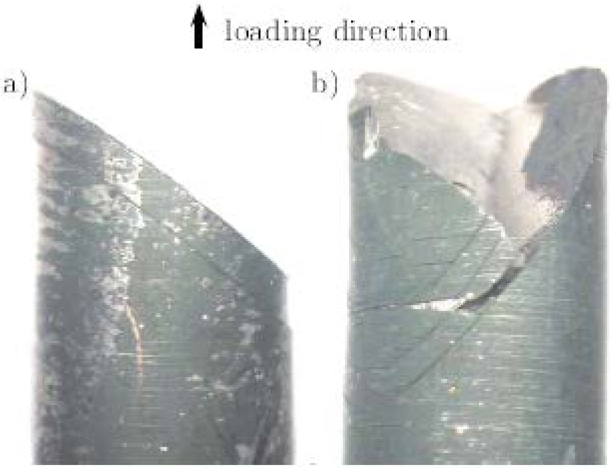


Normalisation

- Normalisation with numerical elastic stiffness



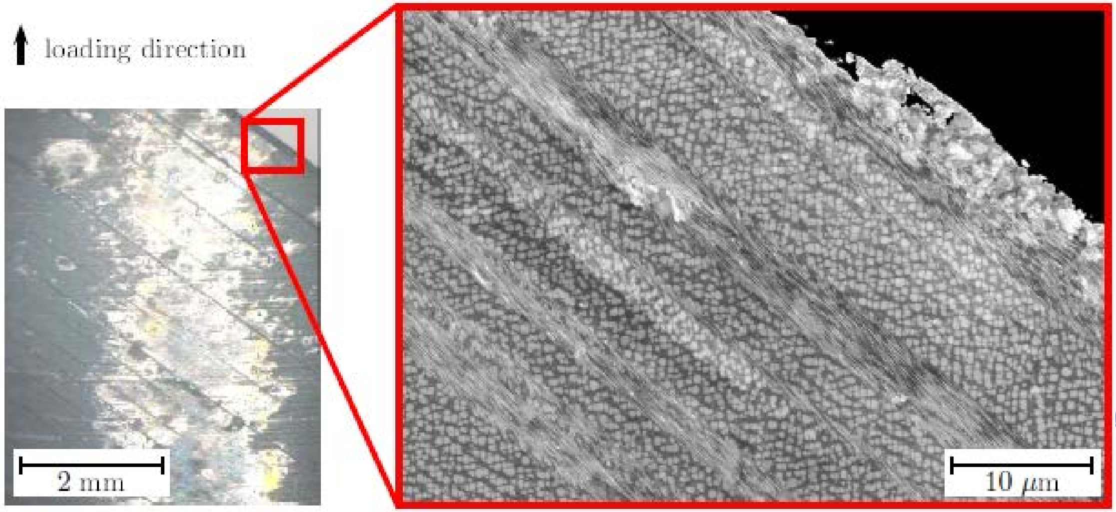
Active slip planes



- Experimental work defined active slip planes.
- Deformation bands was a major deformation mechanism.
- More planes, more evenly distributed stress and longer TMF life.

Table 3: The number of active slip planes (dominant deformation) in each specimen.

Specimen	A	B	C	D	E	F	G	H	I	J	K	L
Active slip planes	3	2	2	2	3	2	1	1	1	1	1	2



ALITY

Numerical active slip plane

α	$\boldsymbol{n}^\alpha$	$\boldsymbol{s}^\alpha$
1	(111)	$[01\bar{1}]$
2	(111)	$[\bar{1}01]$
3	(111)	$[1\bar{1}0]$
4	$(1\bar{1}\bar{1})$	$[0\bar{1}1]$
5	$(1\bar{1}\bar{1})$	$[\bar{1}0\bar{1}]$
6	$(1\bar{1}\bar{1})$	$[110]$
7	$(\bar{1}1\bar{1})$	$[011]$
8	$(\bar{1}1\bar{1})$	$[10\bar{1}]$
9	$(\bar{1}1\bar{1})$	$[\bar{1}\bar{1}0]$
10	$(\bar{1}\bar{1}1)$	$[0\bar{1}\bar{1}]$
11	$(\bar{1}\bar{1}1)$	$[101]$
12	$(\bar{1}\bar{1}1)$	$[\bar{1}10]$

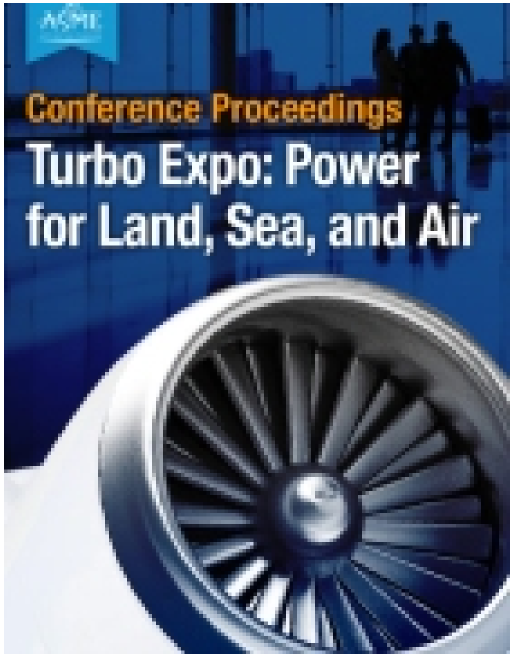
- Projection of stress state, Schmid's law.

$$\tau^\alpha = \boldsymbol{s}^\alpha \cdot \boldsymbol{\sigma} \cdot \boldsymbol{n}^\alpha$$

- Unity or near unity => active slip system.
- Good agreement with experimental observations.

α	τ^α														
	[001]	[011]	[111]	A	B	C	D	E	F	G	H	I	J	K	L
1	1.0	0.0	0.0	0.935	0.978	0.995	0.981	0.981	0.983	0.384	0.390	0.351	0.200	0.232	0.253
2	1.0	1.0	0.0	0.999	0.999	0.999	0.997	0.999	0.999	0.669	0.999	0.640	0.659	0.742	0.665
3	0.0	1.0	0.0	0.065	0.020	0.005	0.016	0.018	0.016	0.285	0.610	0.289	0.459	0.510	0.412
4	1.0	0.0	0.0	0.929	0.975	0.976	0.925	0.955	0.957	0.226	0.389	0.201	0.126	0.162	0.157
5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
6	0.0	1.0	1.0	0.071	0.025	0.024	0.075	0.045	0.044	0.774	0.611	0.799	0.874	0.838	0.843
7	1.0	0.0	1.0	0.935	0.980	0.995	0.984	0.982	0.984	0.715	0.391	0.711	0.542	0.491	0.588
8	1.0	0.0	0.0	0.873	0.956	0.971	0.911	0.938	0.942	0.241	0.242	0.223	0.175	0.187	0.193
9	0.0	0.0	1.0	0.063	0.024	0.024	0.073	0.044	0.042	0.474	0.148	0.488	0.367	0.303	0.395
10	1.0	0.0	1.0	0.928	0.975	0.976	0.922	0.954	0.956	0.105	0.388	0.160	0.215	0.096	0.178
11	1.0	0.0	1.0	0.872	0.956	0.971	0.908	0.937	0.941	0.090	0.241	0.137	0.167	0.071	0.142
12	0.0	0.0	0.0	0.056	0.019	0.005	0.014	0.017	0.015	0.015	0.147	0.023	0.048	0.025	0.036
τ^α_{max} MPa	4.082	4.082	2.722	4.341	4.173	4.141	4.262	4.209	4.201	4.415	4.792	4.332	4.402	4.595	4.429

TMF crack initiation paper



- *Evaluation of thermomechanical fatigue crack initiation in a single-crystal superalloy*
- D. Leidermark
- ASME Turbo Expo 2015, Montréal, Canada

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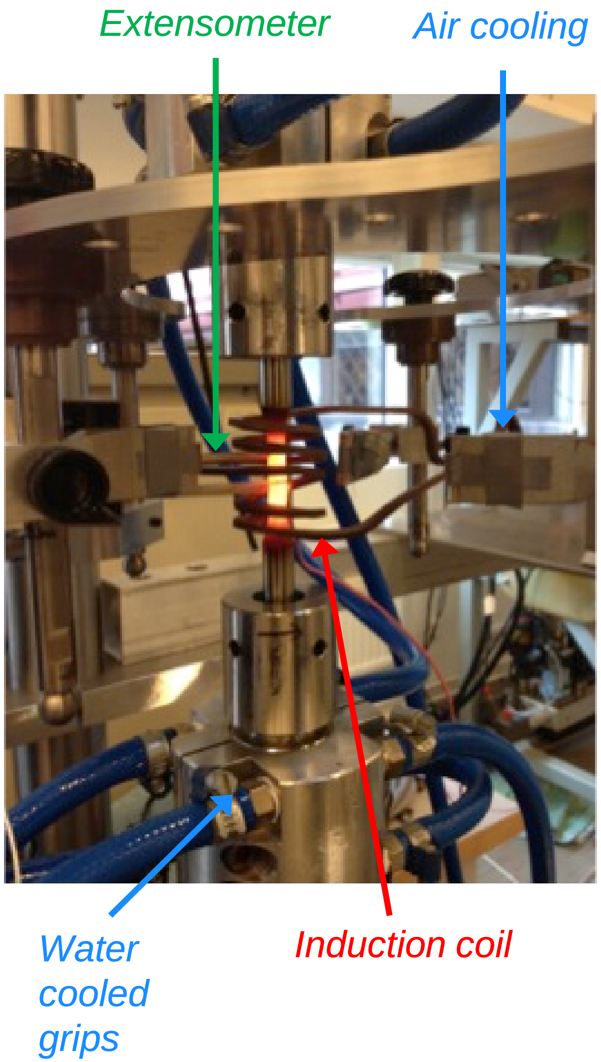
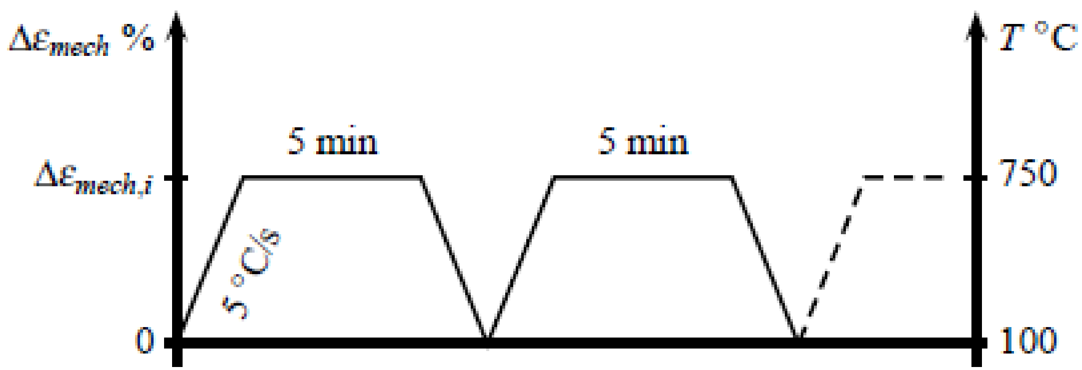


TMF Experiments

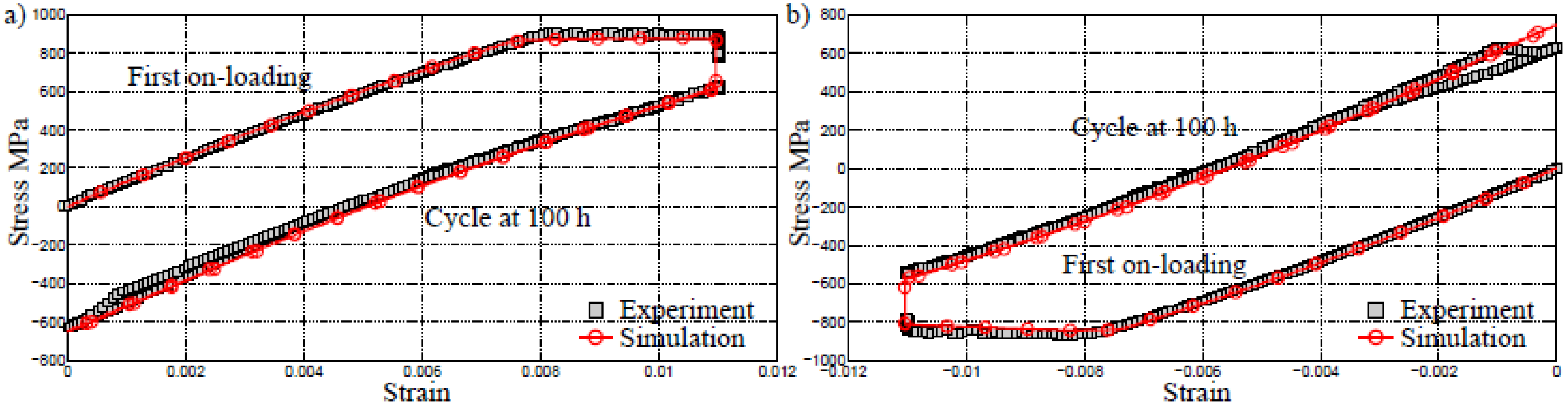
- Eight specimens cycled in IP and OP TMF.
- Nominal [001] & [011] crystal directions.
- Temperature range 100 – 750°C.



Specimen	Diameter mm	$\Delta\varepsilon_{mech,i}$ %	N_i cycles	θ °	ϕ °
$IP1_{[001]}$	6.0	1.1	1085	9.4	31.1
$OP1_{[001]}$	6.0	−1.1	2116	10.2	41.3
$IP2_{[001]}$	6.36	1.25	748	3.3	31.3
$OP2_{[001]}$	6.34	−1.25	285	5.2	6.8
$IP3_{[001]}$	6.0	1.4	238	9.5	22.1
$OP3_{[001]}$	6.29	−1.4	156	4.5	16.5
$IP4_{[011]}$	6.0	0.8	90	41.0	9.1
$OP4_{[011]}$	6.35	−0.8	27	41.2	1.7

Constitutive behaviour

- 5 min hold-time using 100 h hold-time parameters.
- Half-life cycle evaluated.



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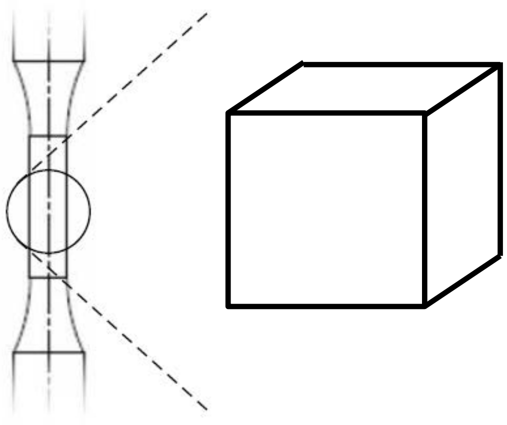
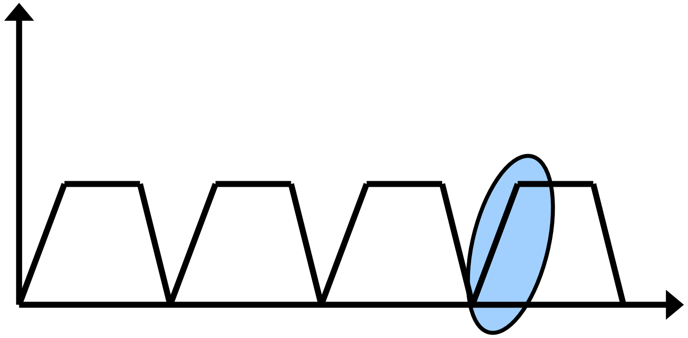
TMF crack initiation evaluation

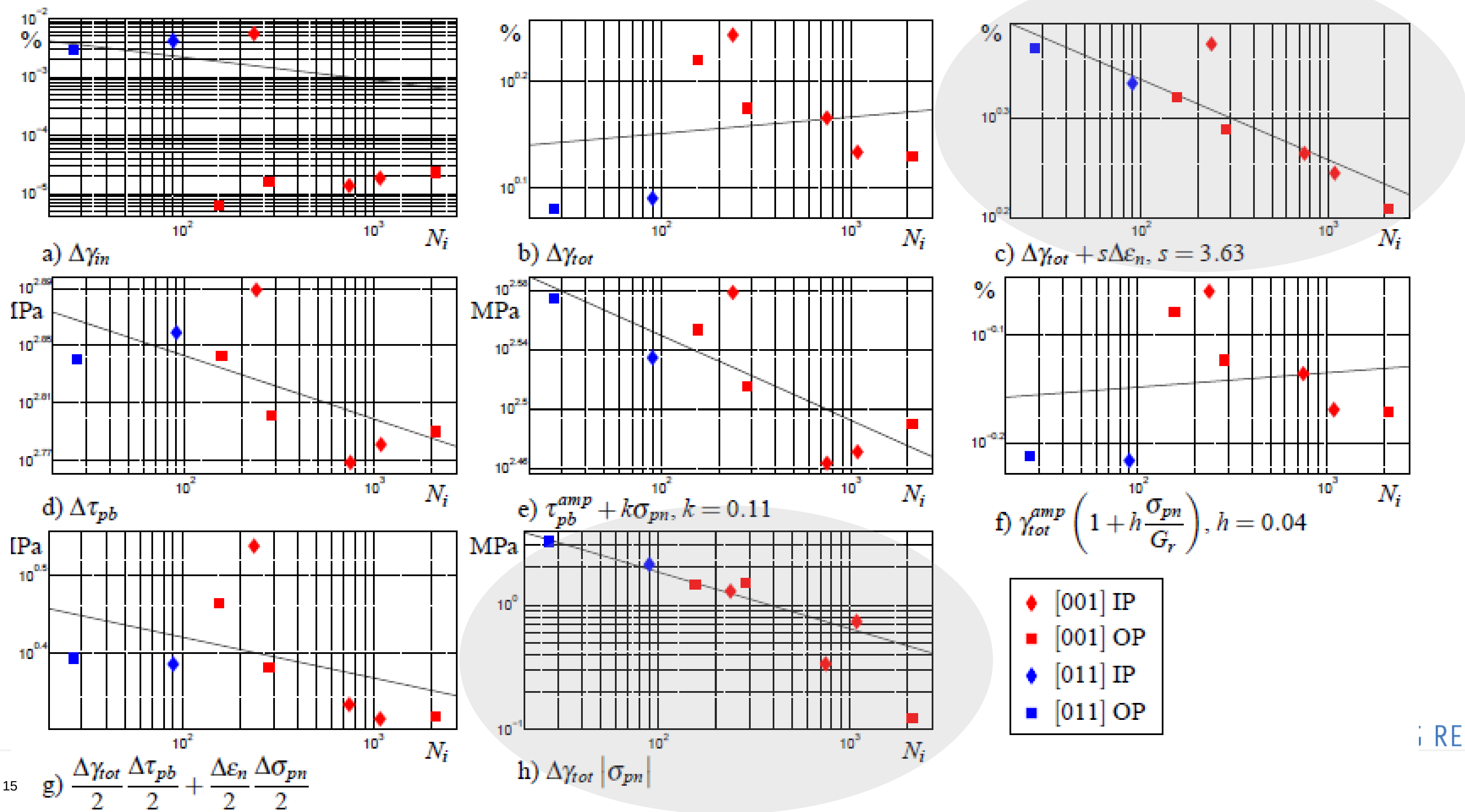
- FE-simulations were performed.
- One eight noded brick element.
- Misalignments of the test specimens were taken into account.
- Crystallographic entities were extracted from the slip planes in the element.





TMF crack initiation evaluation

- Single-crystal inherent internal structure of slip planes => Critical-plane theory



REALITY

Conclusion

- The two emphasised models catches the anisotropy, as well as the tension/compression asymmetry.
- Statistical scatter…

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