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Notch fatigue resistance of shot peened high-strength aluminium alloys:

The role of residual stress relaxation

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Fatigue of high-strength Al alloys

High-strength Al alloys (UTS > 500 MPa) suffer from:

- Low fatigue resistance: ~¼ UTS at $5 \cdot 10^6$ cycles
- High fatigue notch sensitivity: $q = 0.7 \div 0.9$

SOLUTION ?

- Is **controlled shot peening** an effective technological method to improve notch fatigue resistance of high-strength Al alloys?

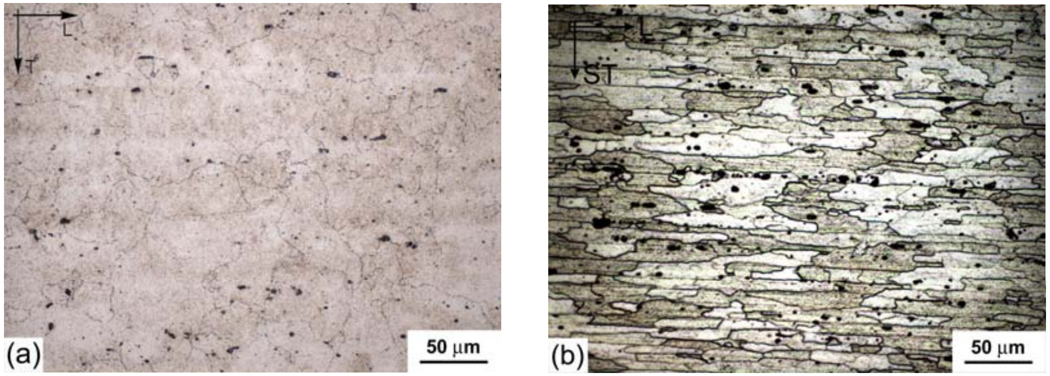
Shot peening and fatigue: open issues

- Residual stresses overcompensate the worsening of microstructure and surface morphology?
- Stability of residual stress state?
- Subsuperficial crack initiation?
- Beneficial effect even in the presence of complex stress states, e.g. in the vicinity of notches?
- Does this beneficial effect depend on the notch severity?
- Adequate coverage of small geometrical details?

Outline

- Experimental material and fatigue tests
- Notch fatigue and notch sensitivity
- Shot peening coverage of notched samples
- Plain fatigue and residual stress relaxation
- FEM reconstruction of the residual stress field in notched specimens
- Notch fatigue and residual stress relaxation

Experimental material: Al-7075-T651



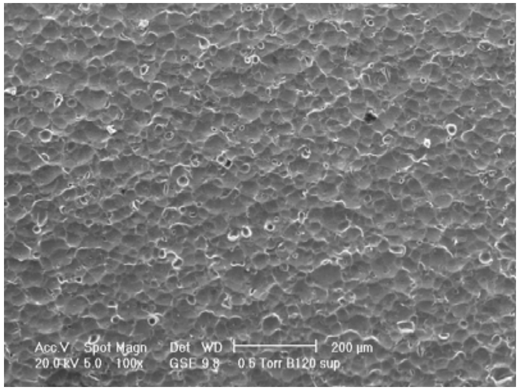
- solution heat treatment for 30 min at 748 K
- water quenching
- stress relief by stretching to give a permanent elongation strain of 2.5%
- final aging at 394 K for 6 h

Monotonic tensile properties					
E (GPa)	$\sigma_{Y0.2}$ (MPa)	UTS (MPa)	σ_F (MPa)	T.E. (%)	R.A. (%)
73 (±1)	510 (±5)	565 (±5)	760 (±10)	18 (±2)	24 (±2)
E: elastic modulus; $\sigma_{Y0.2}$: 0.2% yield stress; UTS: ultimate tensile strength; σ_F: true fracture stress; T.E.: total elongation; R.A.: reduction in area					

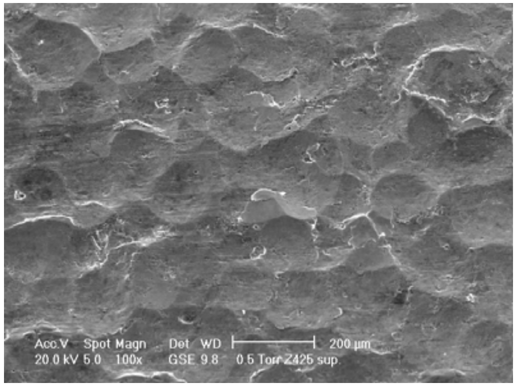
Controlled shot peening treatments

Treatment	Bead size (μm)	Bead hardness (HV_1)	Bead composition	Almen intensity	Bead speed (m/s)	Angle of impingement	Coverage (%)
CE-B120	63-125	700	ZrO_2 67% SiO_2 31%	4.5N	57	90	100
CE-Z425	425-600			4.5A	26		
CE-Comb	CE-Z425 followed by CE-B120						

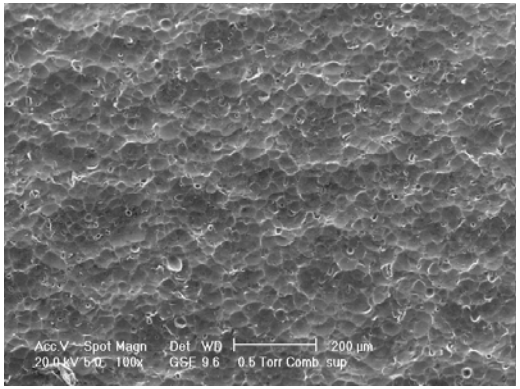
CE-B120



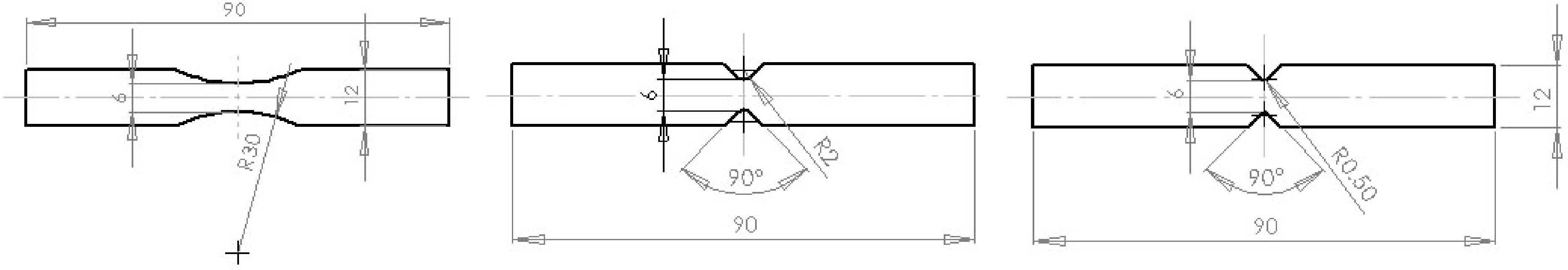
CE-Z425



CE-Comb



Reverse bending fatigue tests



$K_t \approx 1$ $K_t = 1.53$ $K_t = 2.33$

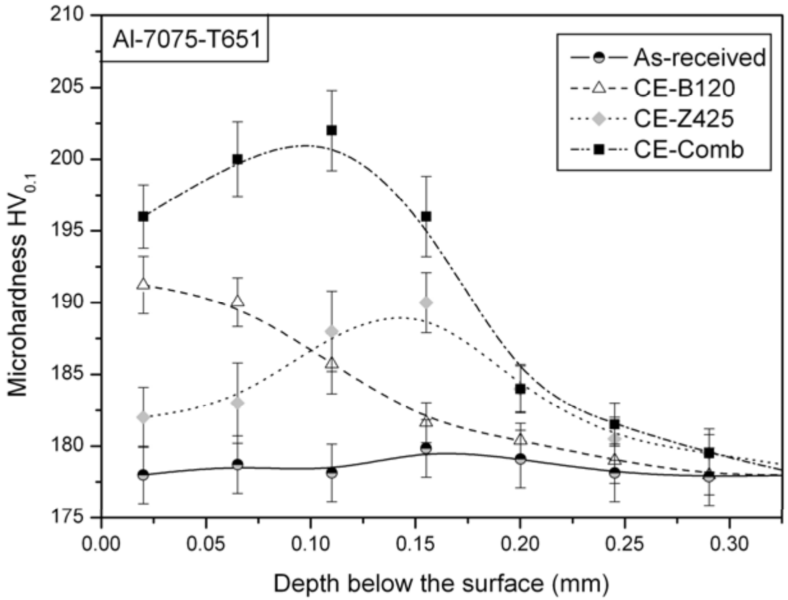
- Reverse (R = -1) plane bending displacement-controlled fatigue tests
- 30 Hz, room temperature
- Fatigue lives ranging between nearly 5×10^4 and 5×10^6 cycles
- The fatigue endurance corresponding to a fatigue life of 5×10^6 cycles was obtained by a staircase procedure, employing 12-15 samples, s = 7 MPa

XRD residual stress measurements on plain samples

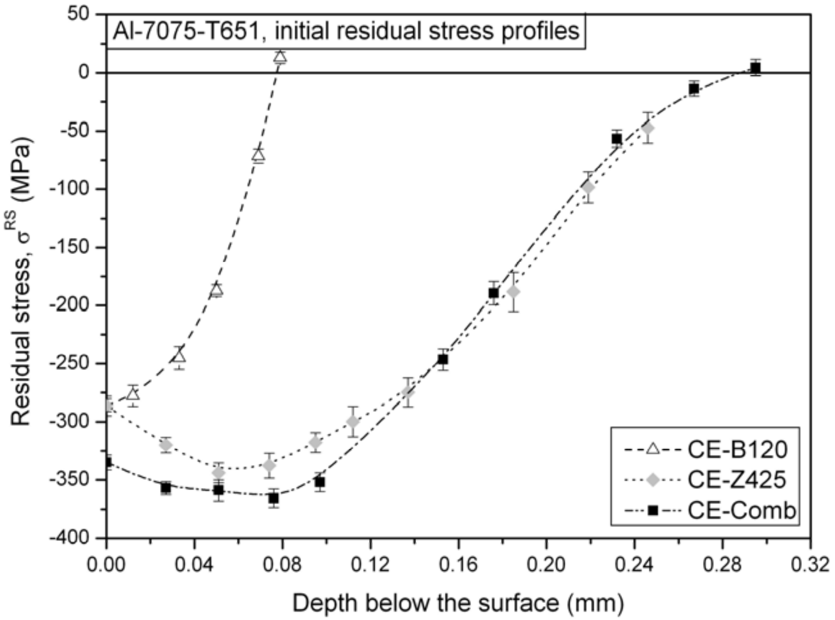
- $\sin^2\psi$ method
- Crystallographic direction <422> to obtain high angle measurements with higher stress sensitivity
- Chemical etching for the progressive thinning of the specimen
- Correction accounting for the effect of the removed layer on the residual stress field was performed according to SAE J748a
- Results obtained by blind hole drilling technique are quite similar
- Stabilized profiles measured on tested specimens after failure in a region far enough from the fracture surface

Surface modifications

Microhardness profiles



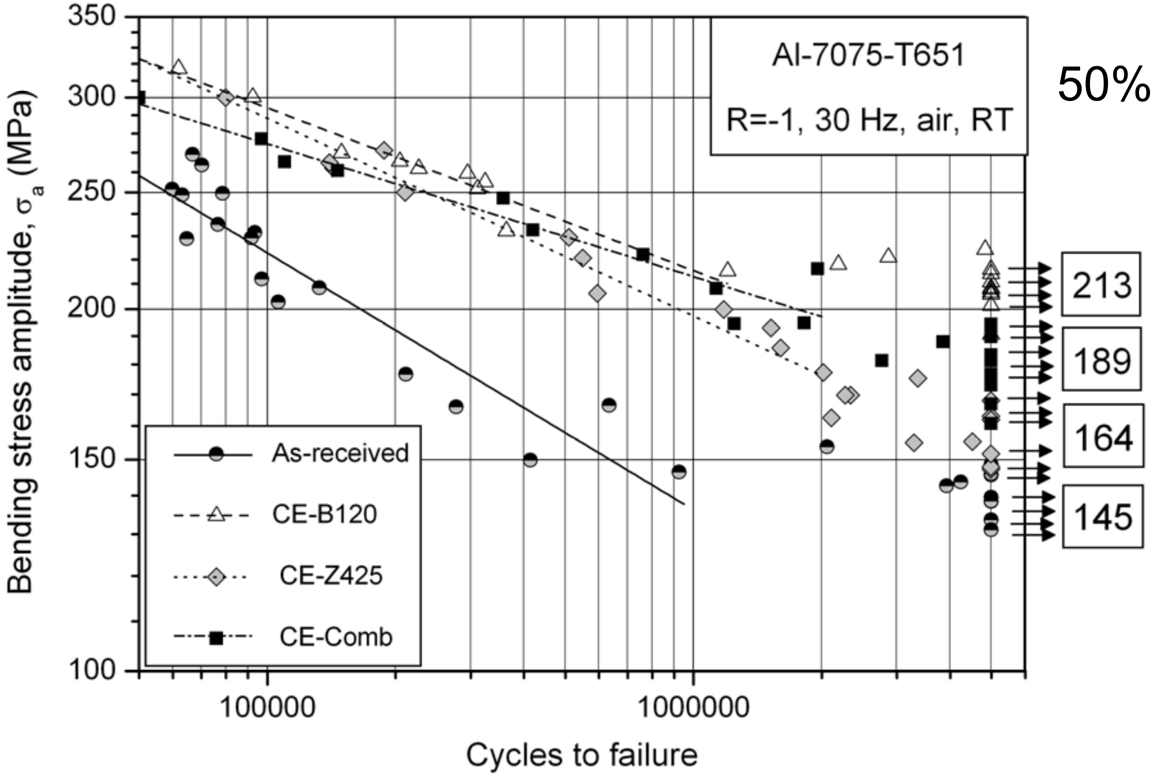
XRD residual stress profiles



Surface roughness

Condition	R_a (µm)	R_q (µm)	R_t (mm)	D_p (µm)	K_t
As-received	0.25	0.30	0.9	-	-
CE-B120	1.35	1.67	6.1	120	1.08
CE-Z425	3.39	4.36	15.2	175	1.17
CE-Comb	3.41	4.37	16.4	190	1.17

Wöhler curves: plain specimens

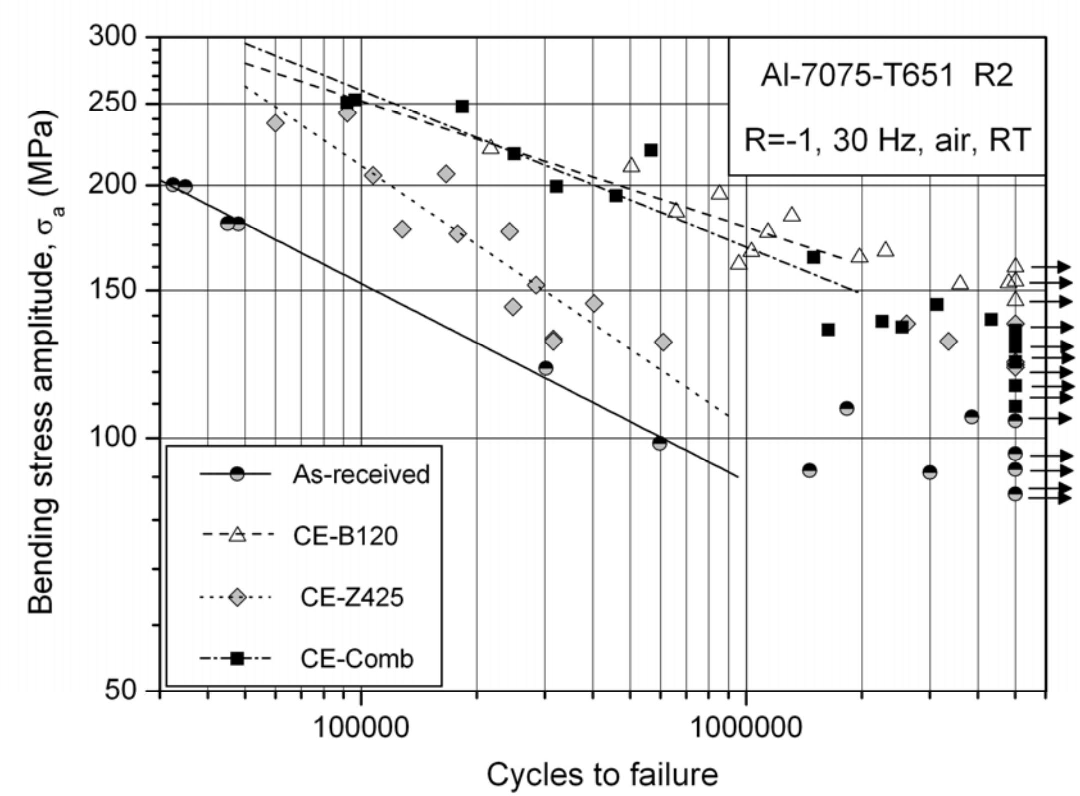


50% failure probability

213	CE-B120
189	CE-Comb
164	CE-Z425
145	As-received

The improvement in the fatigue response is not directly correlated to the treatment intensity and depends on the applied load level

Wöhler curves: R2 specimens

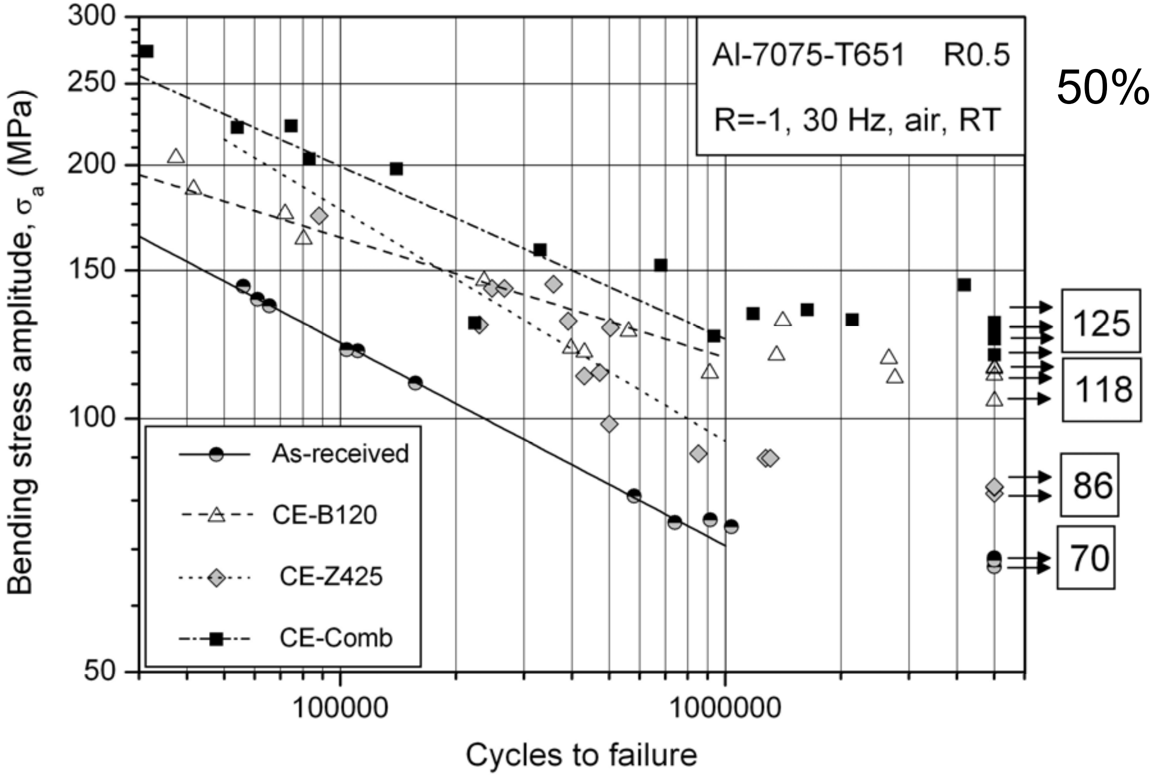


50% failure probability

154	CE-B120
137	CE-Comb
122	CE-Z425
99	As-received

The improvement in the fatigue response is not directly correlated to the treatment intensity and depends on the applied load level

Wöhler curves: R0.5 specimens



50% failure probability

CE-Comb

CE-B120

CE-Z425

As-received

The improvement in the fatigue response is not directly correlated to the treatment intensity and depends on the applied load level

Fatigue notch sensitivity

Condition	Specimen	K_t	K_f	q	a (mm)	Gain $\sigma_{5\cdot 10^6}$ (%)
As received	R2	1.53	1.46	0.88	0.04	-
CE-B120			1.38	0.72	0.29	56
CE-Z425			1.34	0.65	0.58	23
CE-Comb			1.38	0.72	0.31	38
As received	R0.5	2.33	2.07	0.81	0.03	-
CE-B120			1.81	0.61	0.21	69
CE-Z425			1.91	0.68	**0.11**	23
CE-Comb			1.51	0.38	**1.28**	79

$$q = \frac{K_f - 1}{K_t - 1} \qquad q = \frac{1}{1 + \sqrt{\frac{a}{r}}}$$

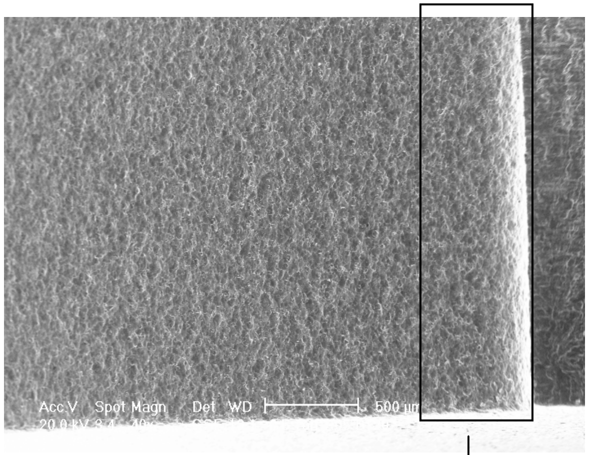
Incomplete coverage?

The increment of the fatigue endurance is more pronounced for sharp notches

Shot peening reduces the fatigue notch sensitivity

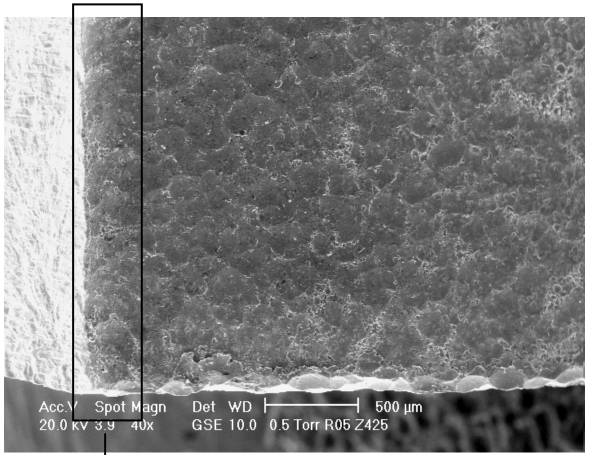
Coverage of sharp notches R0.5

CE-B120



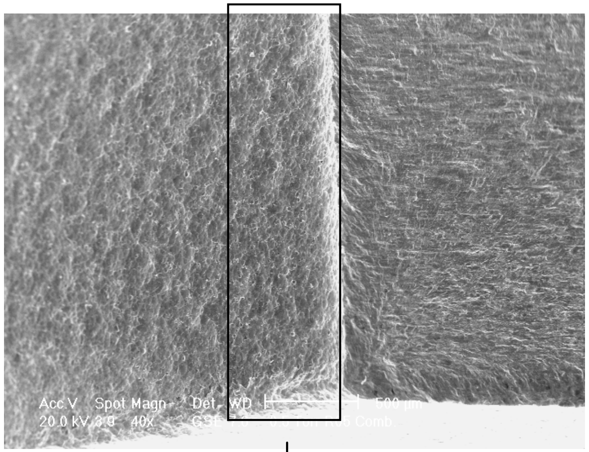
Complete coverage

CE-Z425



No dimples

CE-Comb



Only small dimples

Plain fatigue: the role of residual stress relaxation and fatigue endurance prediction

Why does CE-B120 perform better?

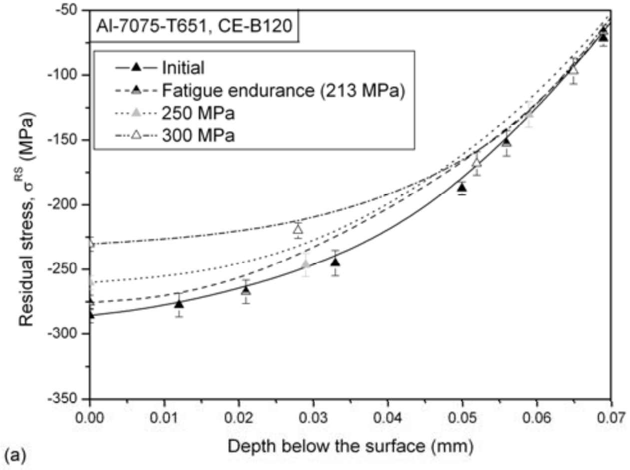
Condition	Surface residual stress (MPa)	Compressive peak residual stress (MPa)	L_{eff} (mm)	Surface microhardness ($HV_{0.1}$)	K_f	$\sigma_{5 \cdot 10^6}$ (MPa)	Gain (%)
CE-B120	-285	-285	0.08	191	1.08	213	47
CE-Z425	-286	-344	0.25	182	1.17	164	13
CE-Comb	-335	-366	0.25	196	1.17	189	30

K_f: fatigue stress concentration factor due to surface dimples

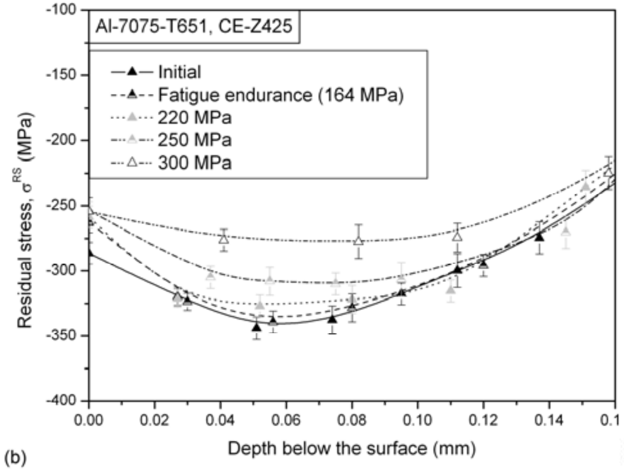
The “gentlest” treatment leads to the highest fatigue endurance, despite lower residual stresses and surface microhardness w.r.t. the more intense treatments

Residual stress relaxation in plane samples

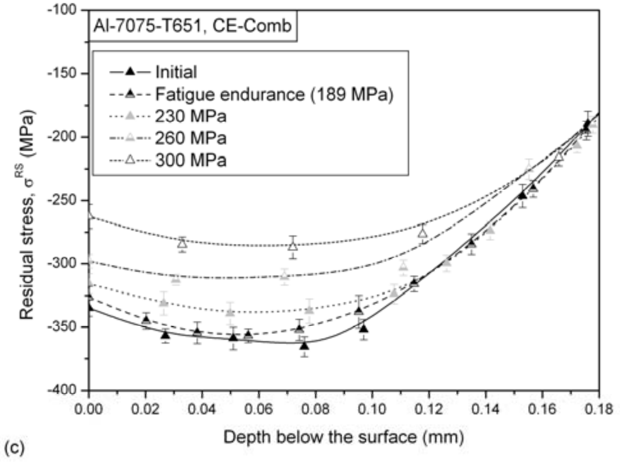
CE-B120



CE-Z425

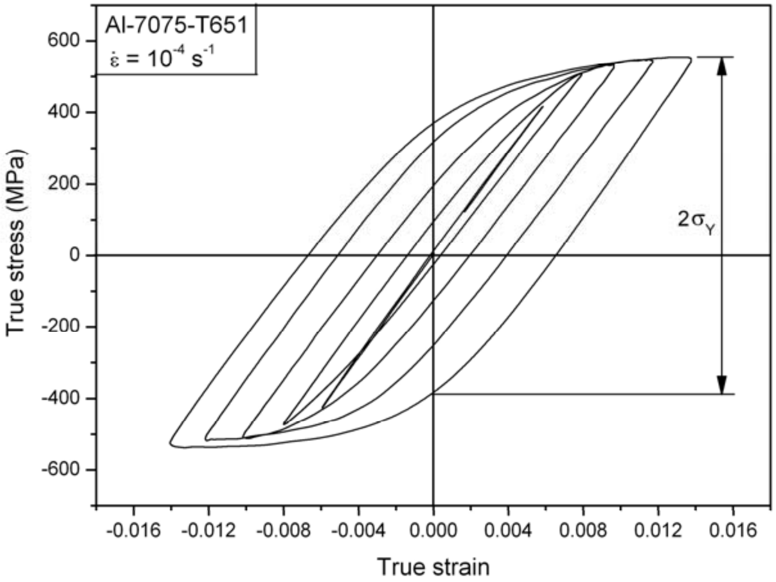


CE-Comb



- No appreciable residual stress relaxation at the fatigue endurance
- Higher loads lead to more pronunced residual stress relaxation
- Is residual stress relaxation induced by plastic deformation during the compressive part of the bending load cycle?

Compression cyclic yield stress vs. microhardness

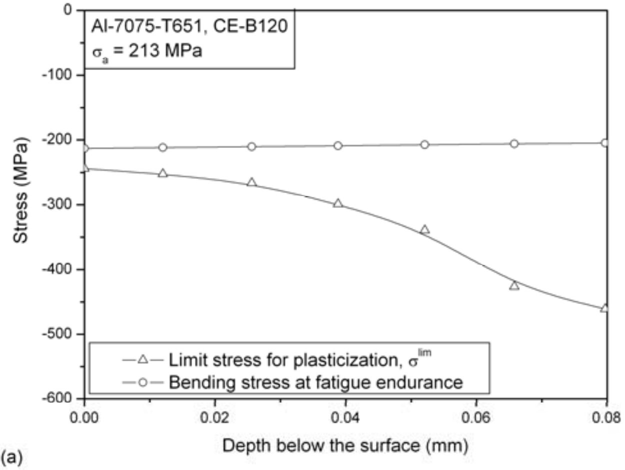


Strain amplitude, ε_a	Microhardness $HV_{0.1}$	Compression cyclic yield stress, $\sigma_{Y,c}$ (MPa)
0.006	179 (as received)	435*
0.008	192	455
0.010	197	470
0.012	201	475
0.014	204	480

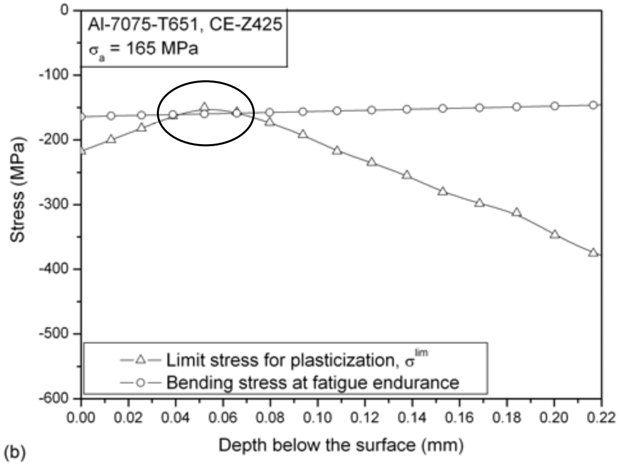
* Compression peak stress

Fatigue endurance and limit stress for plastic flow

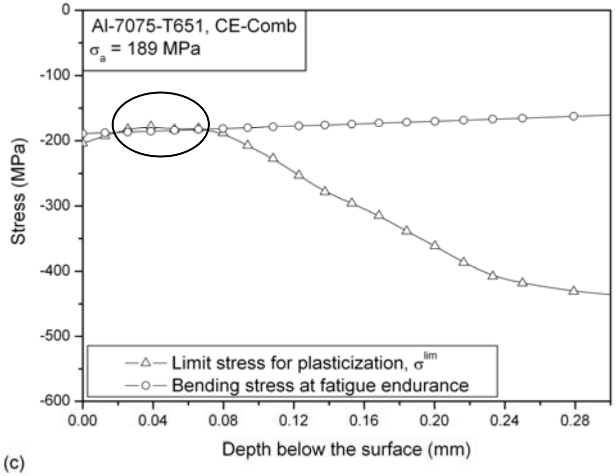
CE-B120



CE-Z425



CE-Comb

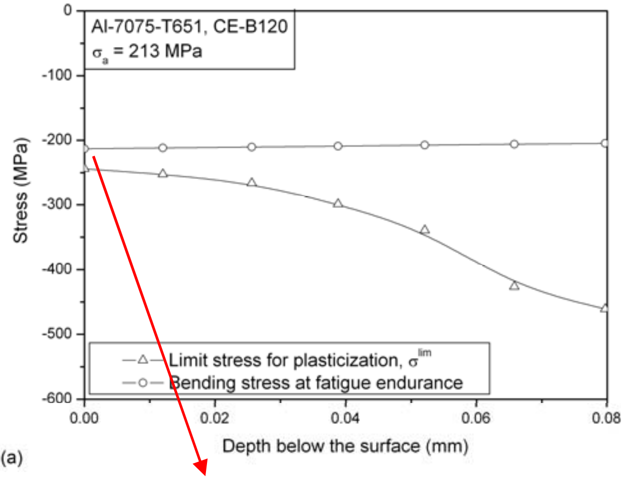


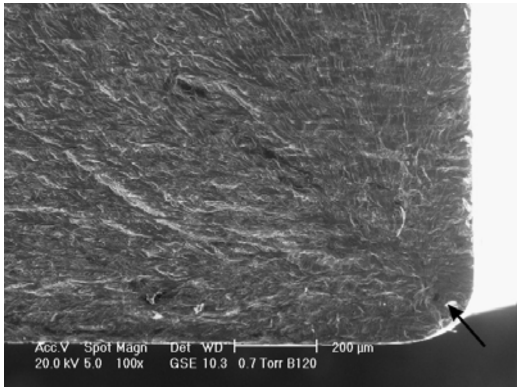
$$\sigma_1^{\lim} = \frac{-\sigma^{RS} - \sqrt{4\sigma_Y^{\,2} - 3\left(\sigma^{RS}\right)^2}}{2}; \quad \sigma_Y = f\left(HV_{0.1}\right)$$

The fatigue endurance of the more intense treatments corresponds to the condition of incipient plastic flow in compression (R=-1)

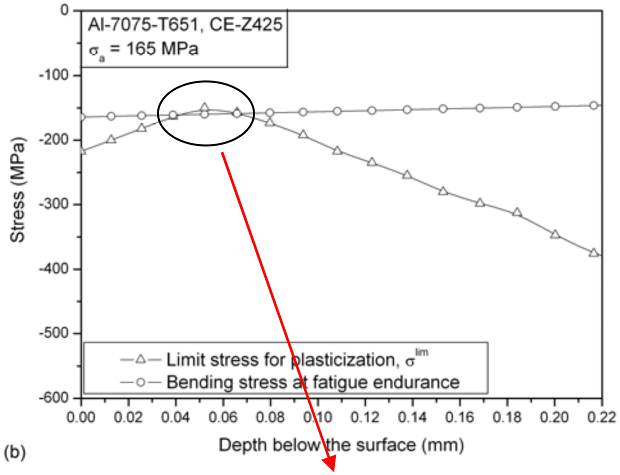
Crack initiation sites at the fatigue endurance

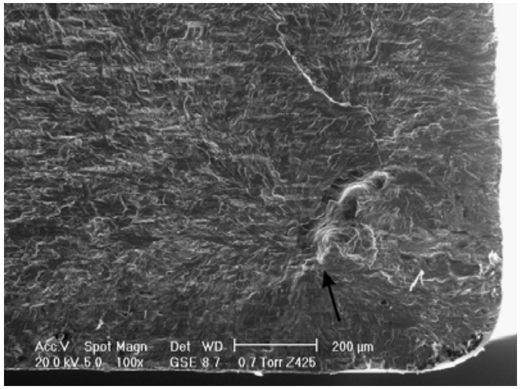
CE-B120



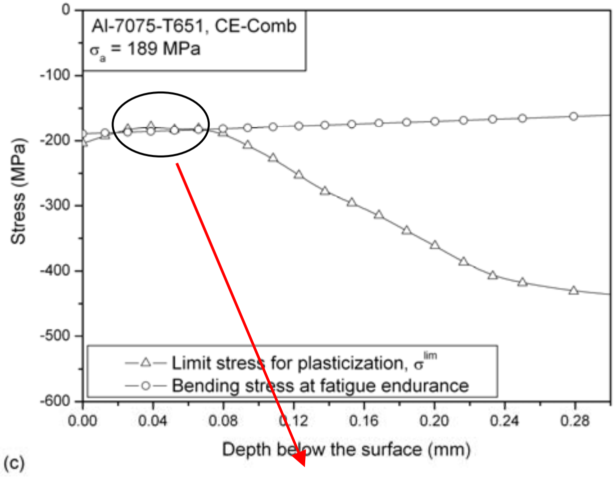


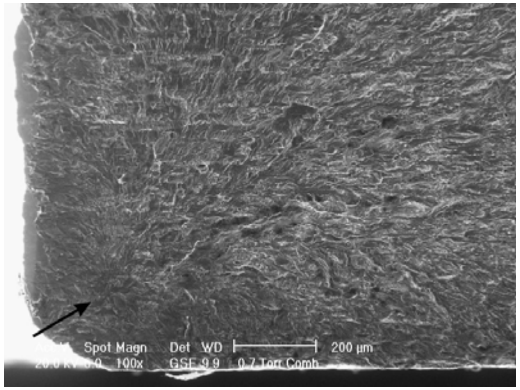
CE-Z425





CE-Comb





Fatigue endurance prediction

Sines fatigue criterion incorporating residual stresses as mean stresses

$$\sigma_{eq,a} + \alpha \cdot p_m = \beta$$

$$\alpha = 3\left(\frac{f_{-1}}{f_0} - 1\right); \quad \beta = \frac{f_{-1}}{K_f}$$

$$\sigma_{eq,a} = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_{1,a} - \sigma_{2,a}\right)^2 + \left(\sigma_{2,a} - \sigma_{3,a}\right)^2 + \left(\sigma_{3,a} - \sigma_{1,a}\right)^2}$$

$$p_m = \frac{\left(\sigma_{1,m} + \sigma_{2,m} + \sigma_{3,m}\right) + \left(\sigma_1^{RS} + \sigma_2^{RS} + \sigma_3^{RS}\right)}{3}$$

Condition	Surface residual stress (MPa)	K$_f$	$\sigma_{5\cdot 10^6}$ (MPa)	
			experimental	predicted
CE-B120	-285	1.08	213	216
CE-Z425	-286	1.17	**164**	**207**
CE-Comb	-335	1.17	**189**	**219**

Fatigue endurance dictated by plastic flow in compression

Notch fatigue: the role of residual stress relaxation and fatigue endurance prediction

Modeling of the residual stress field: basic idea

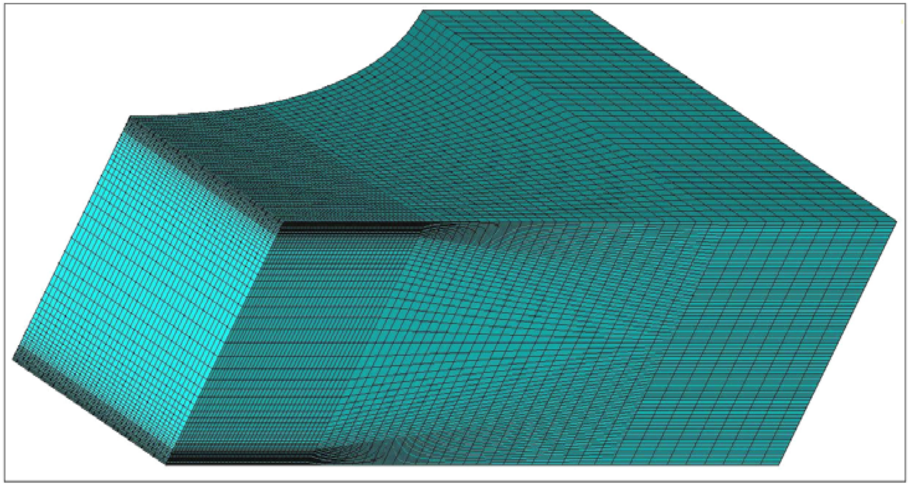
- Fatigue damage is concentrated in a “process zone” ahead the notch tip, characterized by intense stress gradient, whose size is far smaller than the diameter of the X-ray beam used for the XRD measurements (~2 mm)

⇨ FE reconstruction of the residual stress state at the notch tip

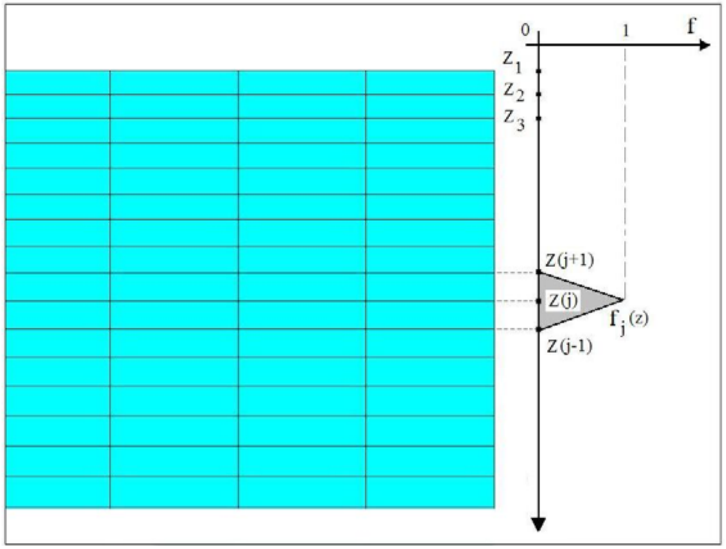
- It was assumed that the residual stress field is induced by a hydrostatic initial strain distribution (ISD), which is only a function of the depth below the treated surface
- ISD is independent of the specimen geometry (plain or notched)
- ISD depends on the shot peening treatment
- ISD created by a fictitious temperature field

Modeling of the residual stress field: FE model

FE model of the plain specimen



Fictitious temperature profile



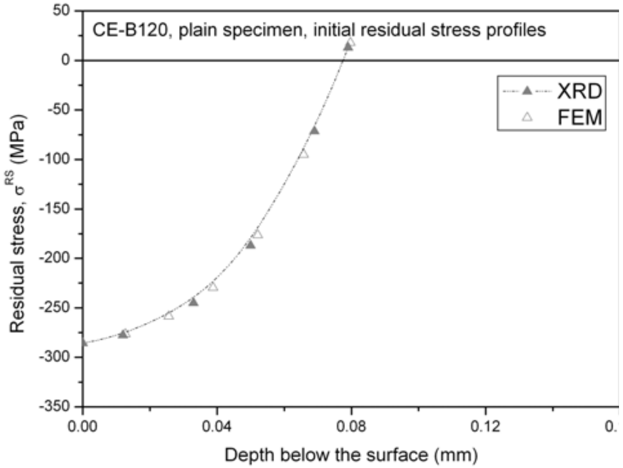
Stress component in the i-th node

$$\sigma_k^i = \sum_{j=1}^{N+1} T_j^* \cdot \boxed{F_j^i} \longrightarrow$$ Influence coefficient determined by FEM

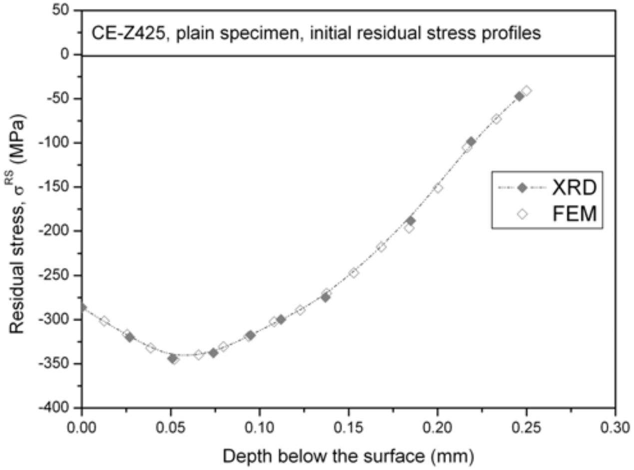
T_j^* calculated by minimizing the square residuals w.r.t. XRD measurements

Modeling of the residual stress field: plain specimens

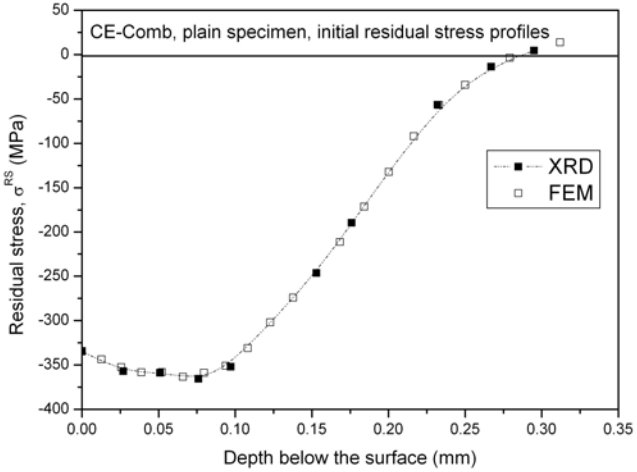
CE-B120



CE-Z425



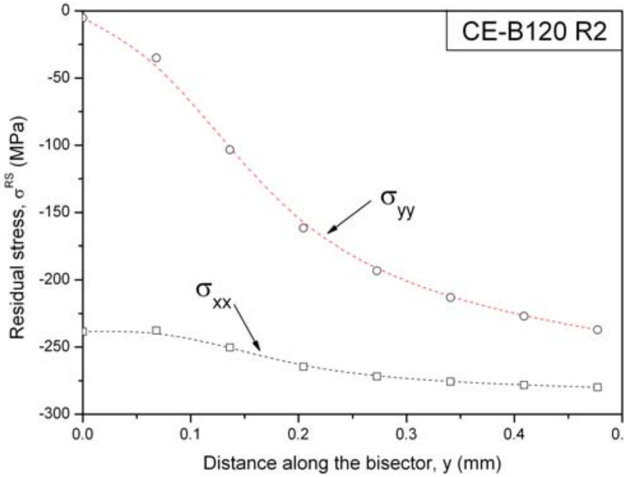
CE-Comb



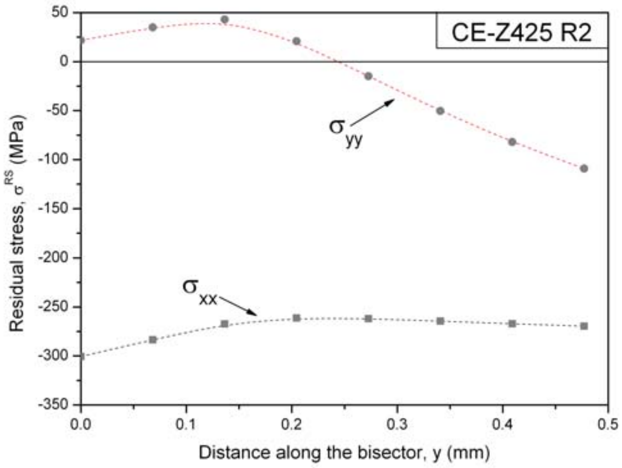
- Good agreement between experimental and numerical residual stress field
- FE analysis confirms equibiaxiality of the residual stress field

Modeling of the residual stress field: notched R2 specimens

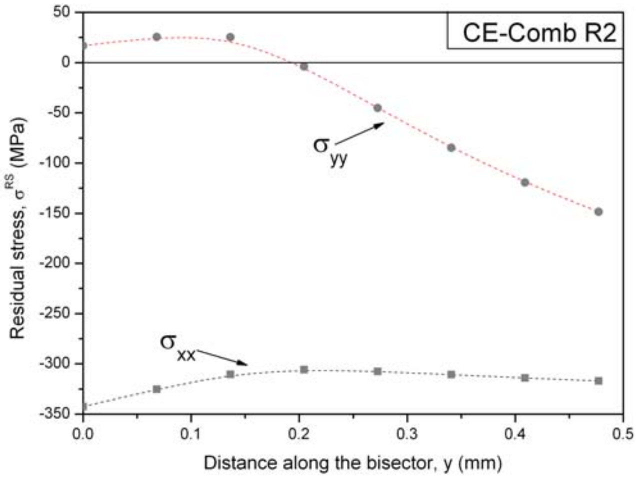
CE-B120

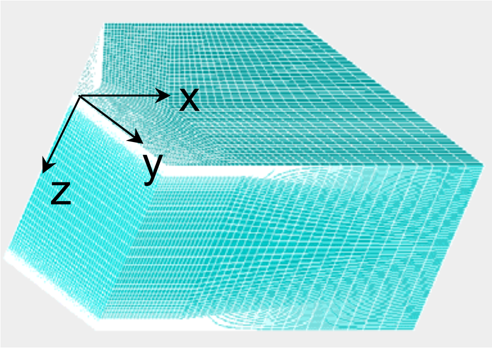


CE-Z425



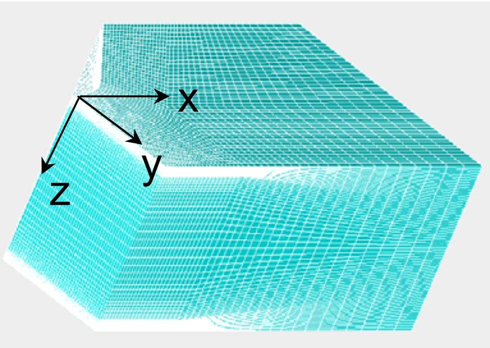
CE-Comb

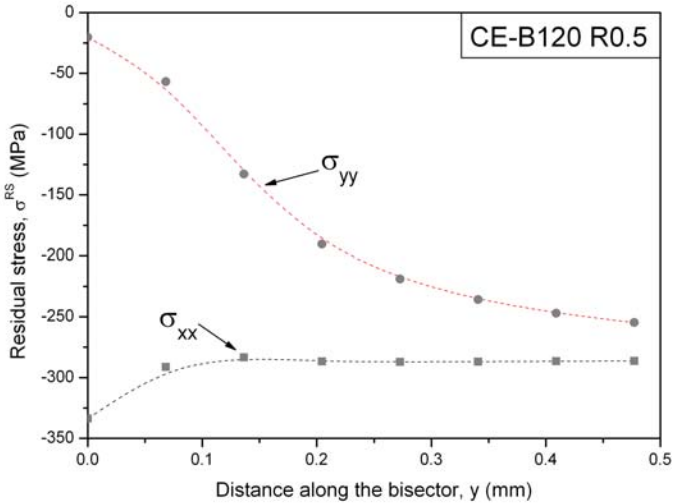




- Uniaxial stress field ahead the notch tip
- Biaxial stress field far from the notch

Modeling of the residual stress field: notched R0.5 specimens

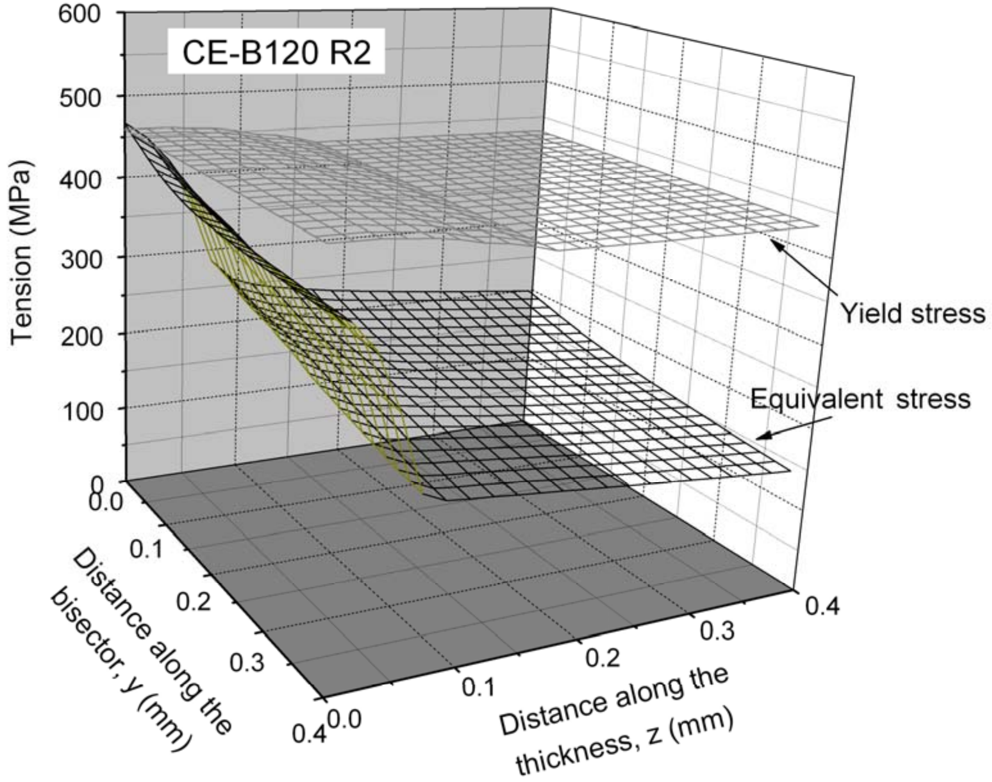




- CE-Z425 and CE-Comb not modelled because of incomplete coverage (ISD unknown)
- Uniaxial stress field ahead the notch tip
- Intensification of the residual stress field in the notch region
- Near equibiaxial stress field far from the notch

Equivalent stress vs. yield stress at the fatigue endurance

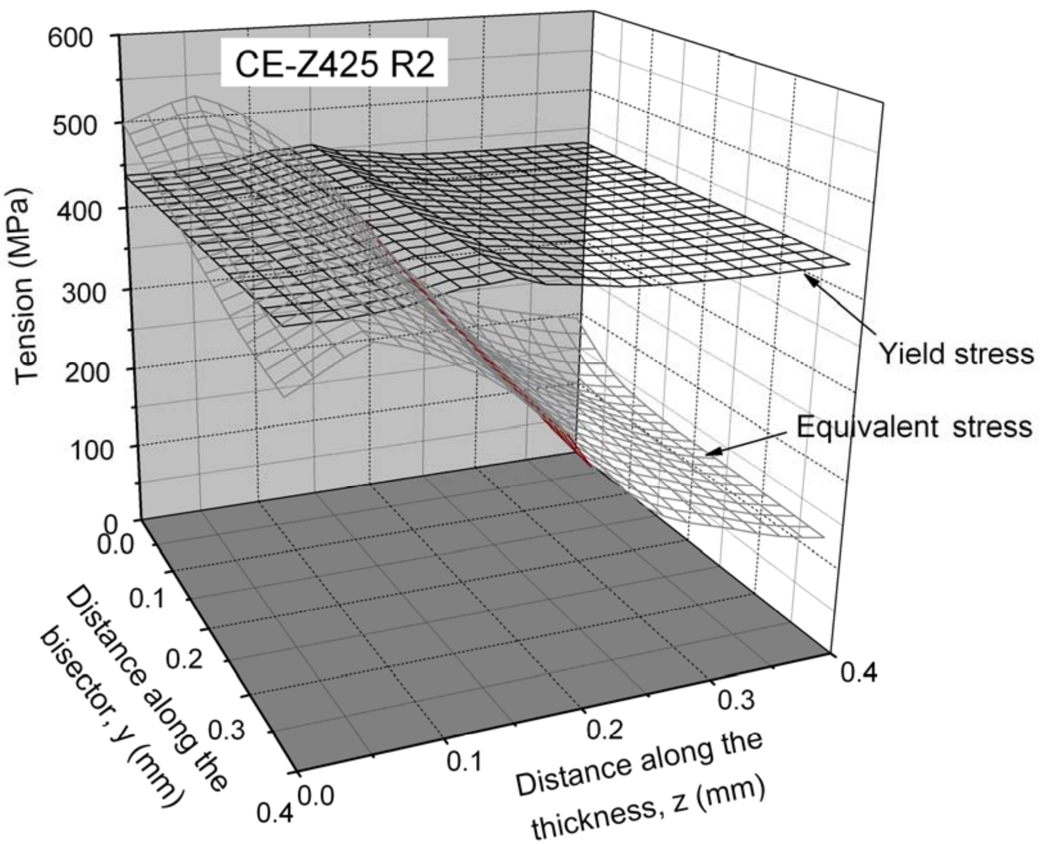
CE-B120 R2



The stress field remains in elastic regime

Equivalent stress vs. yield stress at the fatigue endurance

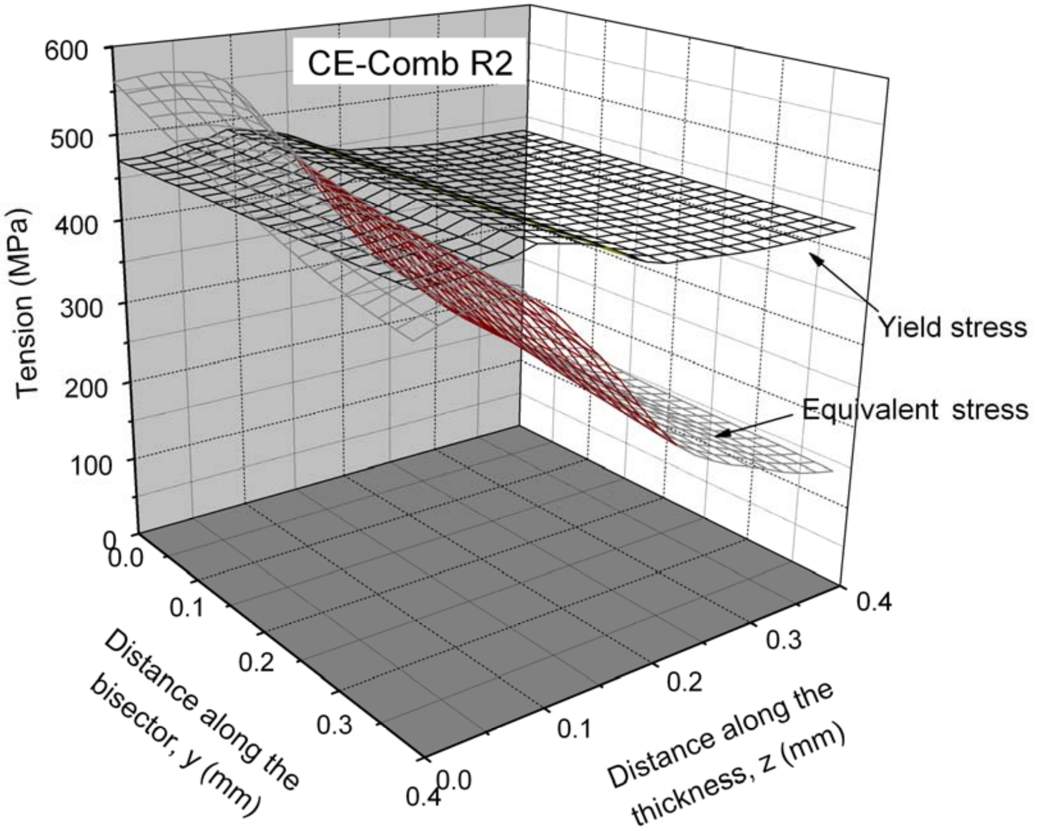
CE-Z425 R2



Equivalent stress exceeds the yields stress in a 0.2 mm region around the notch tip

Equivalent stress vs. yield stress at the fatigue endurance

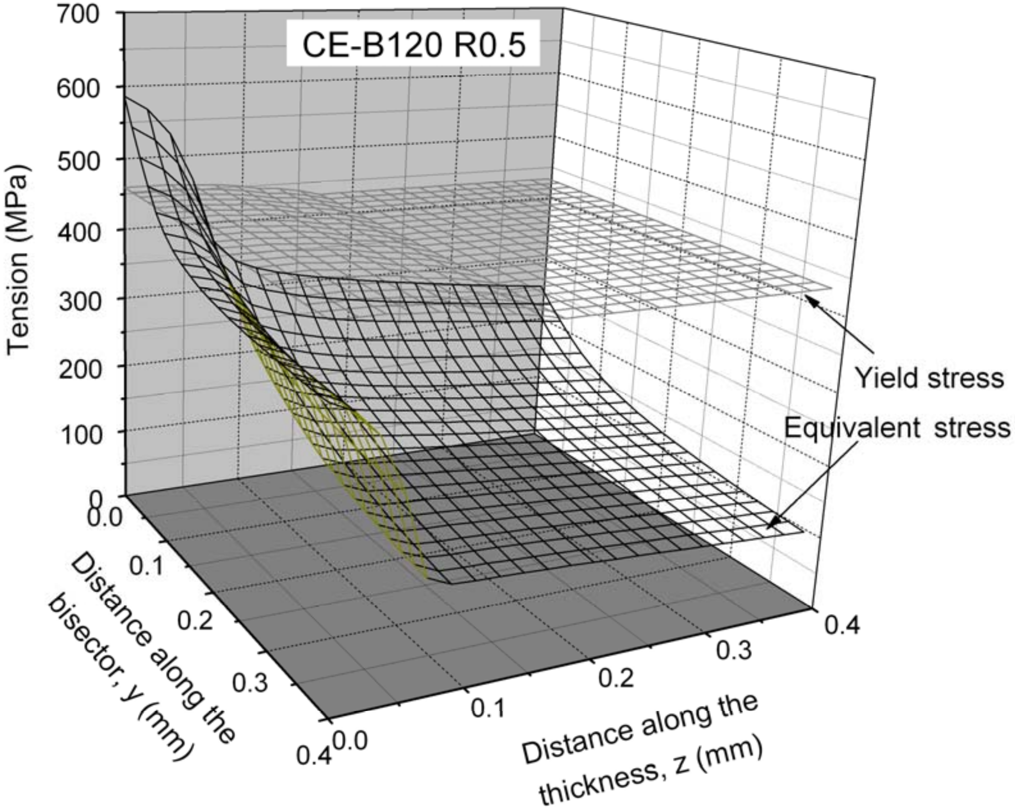
CE-Comb R2



Equivalent stress exceeds the yields stress in a 0.2 mm region around the notch tip

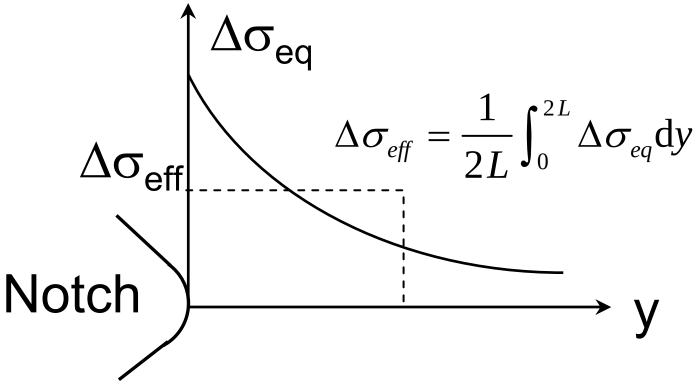
Equivalent stress vs. yield stress at the fatigue endurance

CE-B120 R0.5



Equivalent stress exceeds the yields stress in a 0.1 mm region around the notch tip

*Notch fatigue endurance prediction: the line method**



$$\Delta\sigma_{eff} = \frac{1}{2L}\int_0^{2L} \Delta\sigma_{eq}\,dy$$

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_{\lim}}\right) \cong 0.03\text{mm}$$ El-Haddad length

$\Delta\sigma_{eq}$: equivalent stress according to the Sines criterion incorporating residual stresses as mean stresses

Condition	Specimen	$\sigma_{5\cdot10^6}$ (MPa)		Error (%)
		Experimental	Predicted	
As received	R2	99	98	-1
	R0.5	70	74	6
CE-B120	R2	154	144	-6
	R0.5	118	116	-1
CE-Z425	R2	122	141	**16**
CE-Comb	R2	137	149	**9**

} Fatigue endurance dictated by plastic flow in compression?

*S. Susmel, “The theory of critical distances: a review of its applications in fatigue”, Engng. Fract. Mech., 2008

Concluding remarks

- Shot peening is an effective method to improve the fatigue endurance of Al-alloys even in the presence of geometrical discontinuities

- The fatigue improvement is more pronounced with increasing stress concentration

- Shot peening reduces the fatigue notch sensitivity by about 10%

- Shot peening is more effective, leading to complete coverage of the notch root region, when the shot size is 10 times smaller than the characteristic length of the notch

- Residual stress relaxation due to plastic flow during the compressive part of the loading cycle is a limiting factor for the fatigue endurance

- The fatigue endurance can be accurately predicted by a multiaxial fatigue criterion combined with a line method to account for the notch sensitivity, provided that no (very small) plastic deformation occurs

Future developments

- FE modelling of the residual stress relaxation by taking into account the cyclic elasto-plastic properties of the material in order to confirm the hypothesis that residual stress relaxation is a “quasi-static” effect

- Residual stresses and prediction of the fatigue response in the low cycle regime

- Pulsanting (R=0) bending fatigue tests in order to evaluate the effectiveness of the shot peening treatments without the limiting factor given by the residual stress relaxation in compression. Could CE-Comb perform better than CE-B120 in this case?