

ON PLASTIC NOTCH EFFECTS IN QUENCHED AND TEMPERED STEELS

P. Russo Spina¹, D. Firrao², P. Matteis²

¹Politecnico di Torino, Dipartimento di Sistemi di Produzione ed Economia dell'Azienda

²Politecnico di Torino, Dipartimento di Scienza dei Materiali ed Ingegneria Chimica



Prof. Donato Firrao

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Introduction

In 1971, Firrao and Spretnak compared the elastic-plastic Stress Concentration Factor (SCF) at fracture, k_{pf} , with the elastic SCF, k_e , and the tempering temperature, T , of Q&T steel sheet tensile samples with variable notch tip radius.

1971

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REPORT

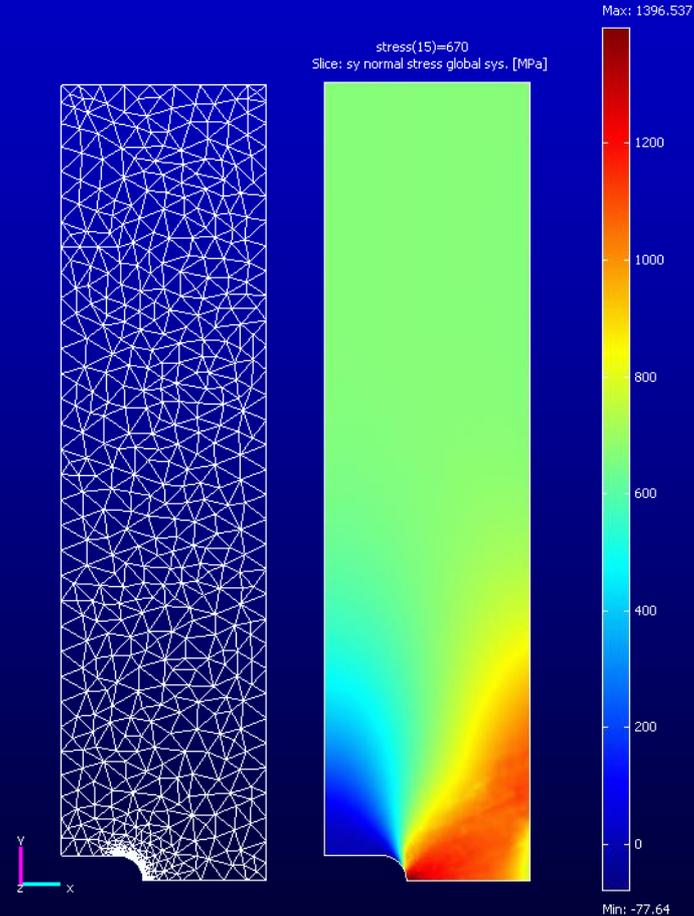
By
THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION
1314 KINNEAR RD.
COLUMBUS, OHIO 43212

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On: AN EVALUATION OF THE GERARD-PAPIRNO
CHARACTERIZATION OF NOTCH DUCTILITY IN
HIGH STRENGTH AISI 4340 STEEL

Submitted by: Donato Firrao and Joseph W. Spretnak
Department of Metallurgical Engineering

Date February 28, 1971



2009

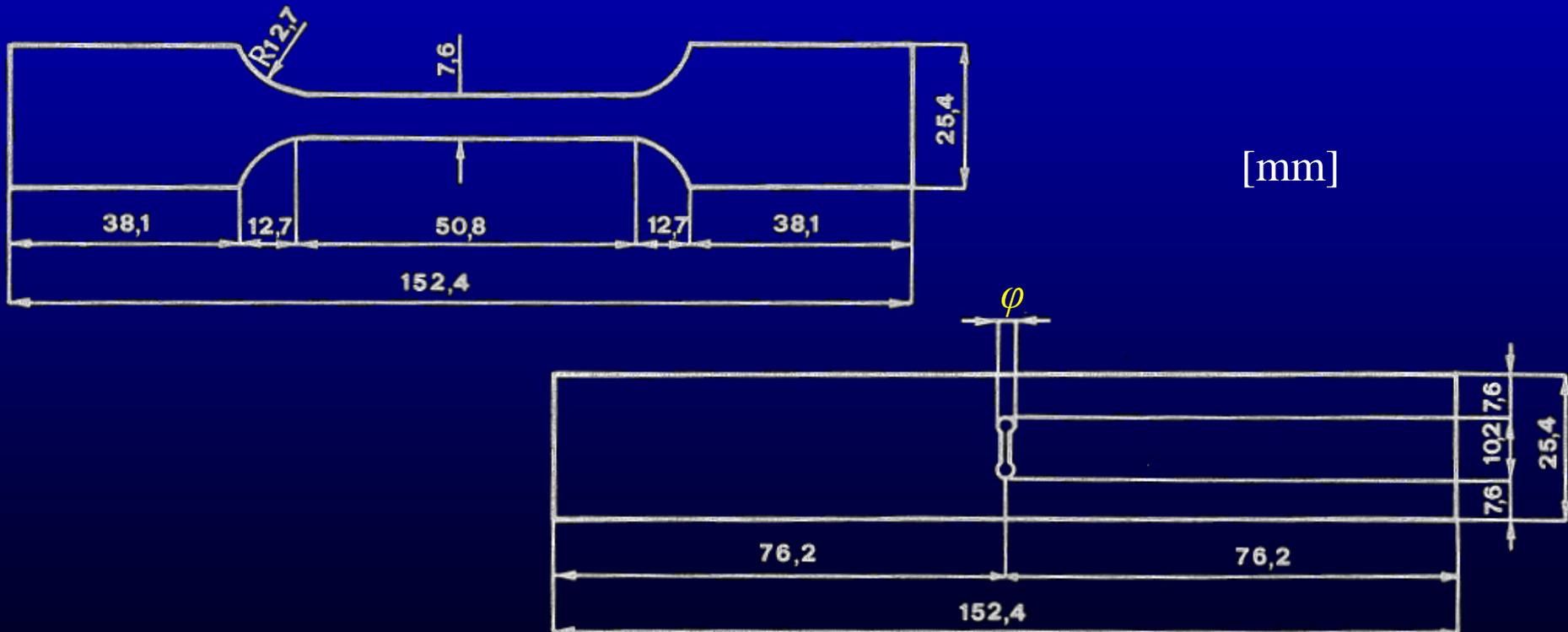
Finite Element calculations now allows to review their test results by overcoming the simplifying assumptions originally used to estimate k_e and k_{pf} .

Specimen preparation (I)

- The AISI 4340 (% wt.) steel was cold-rolled to 1.78 mm sheet and annealed

C	Mn	Cr	Ni	Mo	Cu	P	S
0.37	0.7	0.85	1.91	0.23	0.10	0.013	0.007

- 1.14 mm thick**, smooth or notched tensile samples, were machined from the sheet
- The notches were machined by EDM with tip diameters, ϕ , from 0.13 to 3.17 mm

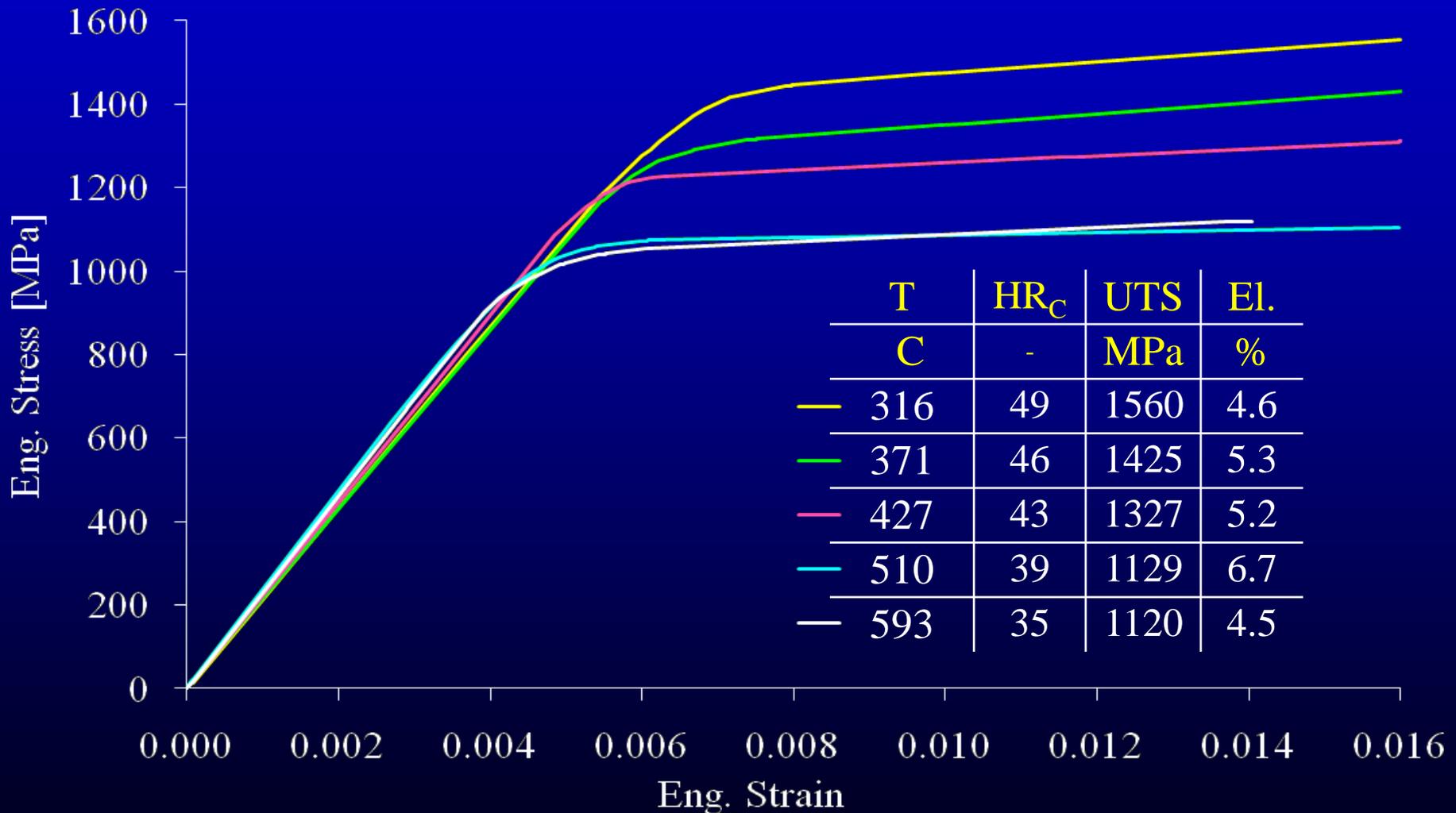


Specimen preparation (II)

- The samples were **austenitized at 843 °C for 30 min and quenched**
- This was done in salt baths and inside clamps, with steps at 704 °C for 20 min during heating and at 204 °C for 5 min during quenching, to minimize deformations and surface alterations
- The samples were then reheated at 177 °C for 1 h, **tempered at $T = 316$ °C for 2.5 h, or $T = 371, 427, 510$ or 593 °C for 2 h, and cooled in air**
- **5 smooth samples and 27 notched samples with different notch diameters were tested for each tempering temperature – total: 160 samples**

Smooth tensile test results

- The fracture always occurred on a surface inclined of $\sim 35^\circ$ from the tensile axis
- Necking did not contribute significantly to the elongation at fracture (El.)
- The strain was recorded with extensometers up to $\varepsilon \approx 0.016$



Finite Elements models of notched samples

3D models:

- 1/8 of the sample central region modeled with tetrahedral elements
- 9 meshes with notch diameters φ from 0.125 to 3.18 mm
- Elements size 20 - 50 μm around the notch (varying with φ), up to 1 mm elsewhere
- 70,000 to 160,000 degrees of freedom (varying with φ)

Boundary conditions:

- Remote stress and symmetry planes
- Engineering stress σ defined in respect to the minimum undeformed cross section

Elastic or Elastic–Plastic material model:

- $E = 200 \text{ GPa}$ and $\nu = 0.33$
- Von Mises yielding criterion, associated plastic flow law, isotropic hardening
- Plastic flow stress vs. equivalent plastic strain curves obtained from the smooth tensile tests, for each T , extrapolated up to 0.1 – 0.6 eq. plastic strain

Elastic-plastic loading:

- 75 MPa σ steps, up to above the largest experimental fracture stress (σ_f), for each T

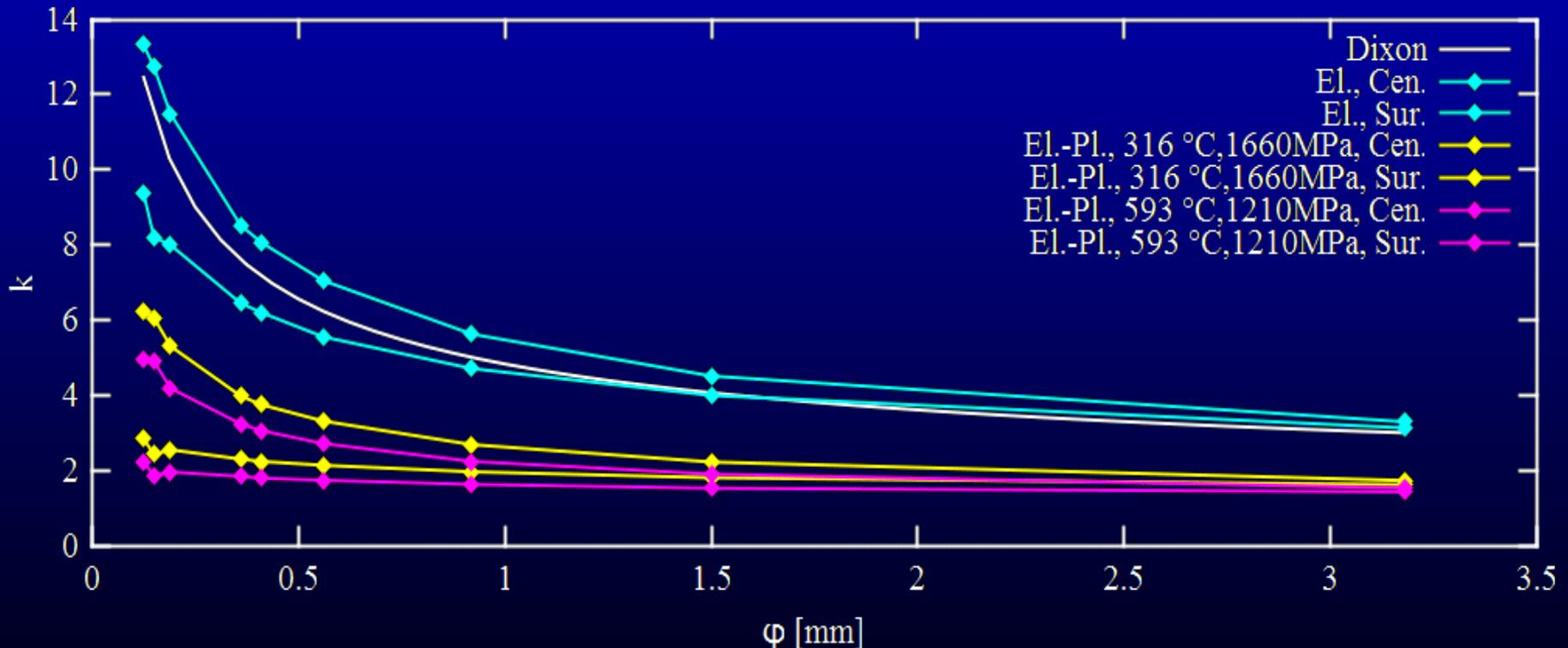
Fracture NOT modeled - 45 independent FE calculations

Stress Concentration Factors (I)

Firrao and Spretnak estimated k_e by using the Dixon plane stress formula, where a is the notch half-width (5.08 mm) and W is the sample width (25.4 mm):

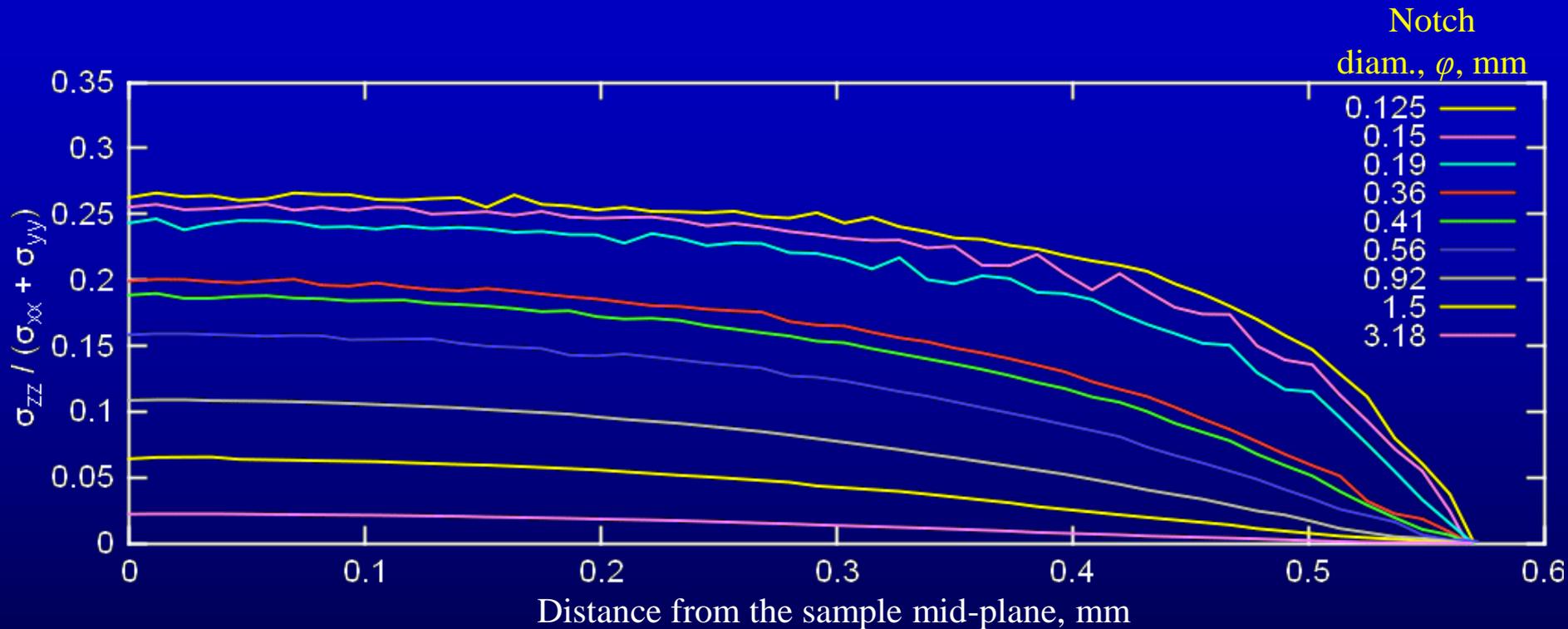
$$k_e = \frac{\sigma_{yy}}{\sigma} = \left(1 + 2 \left(\frac{2a}{\phi} \right)^{1/2} \right) \cdot \frac{1 - 2a/W}{1 + 2a/W}$$

This is compared with the SCF calculated by FE at surface (Sur.) or mid-plane (Cen.), in the elastic (El.) case or in selected Elastic-Plastic (El.-Pl.) ones:



Triaxiality ratios

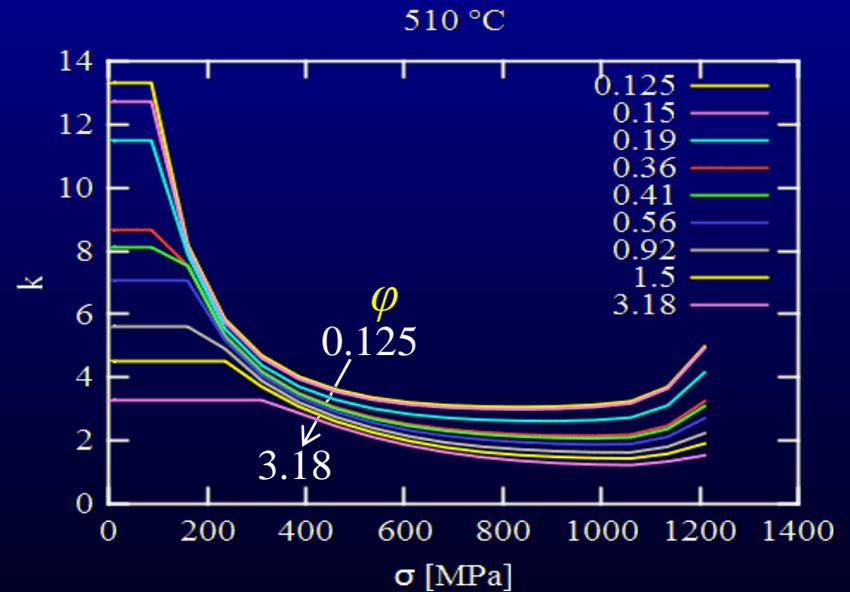
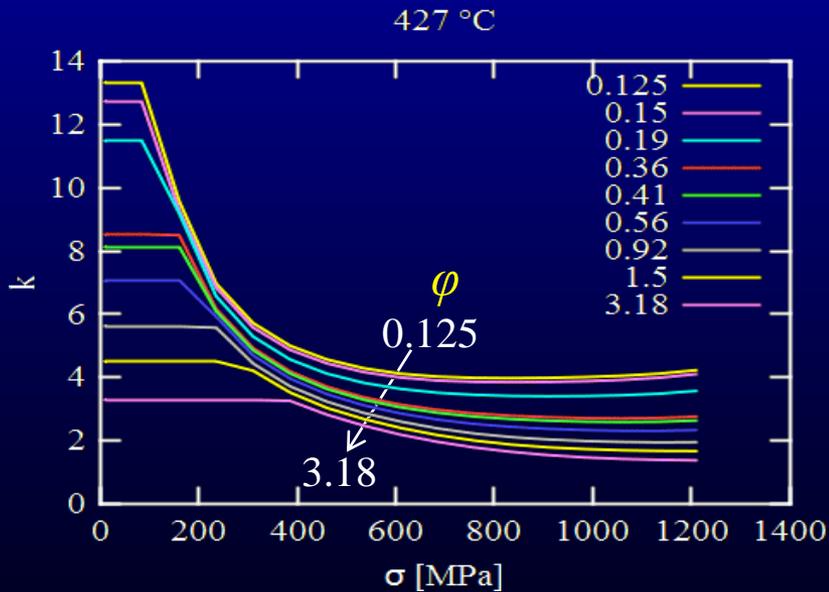
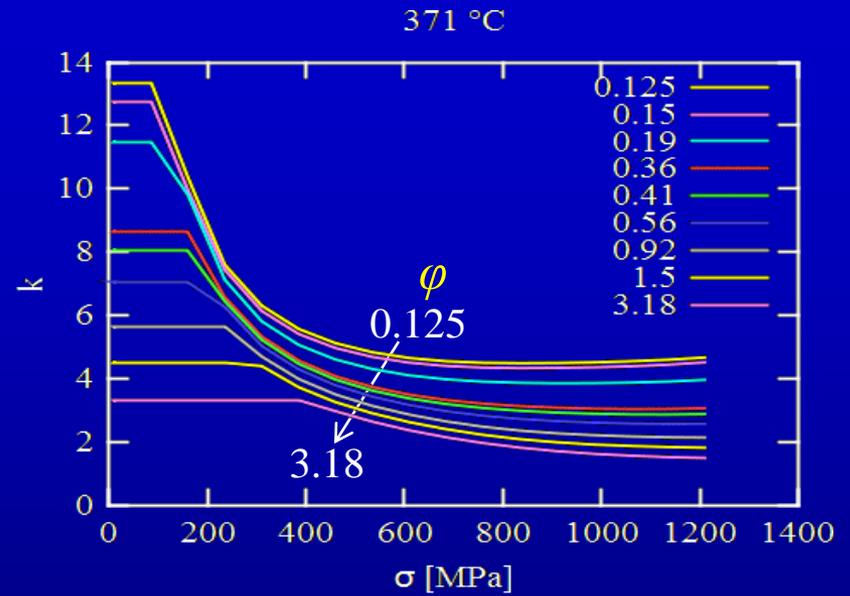
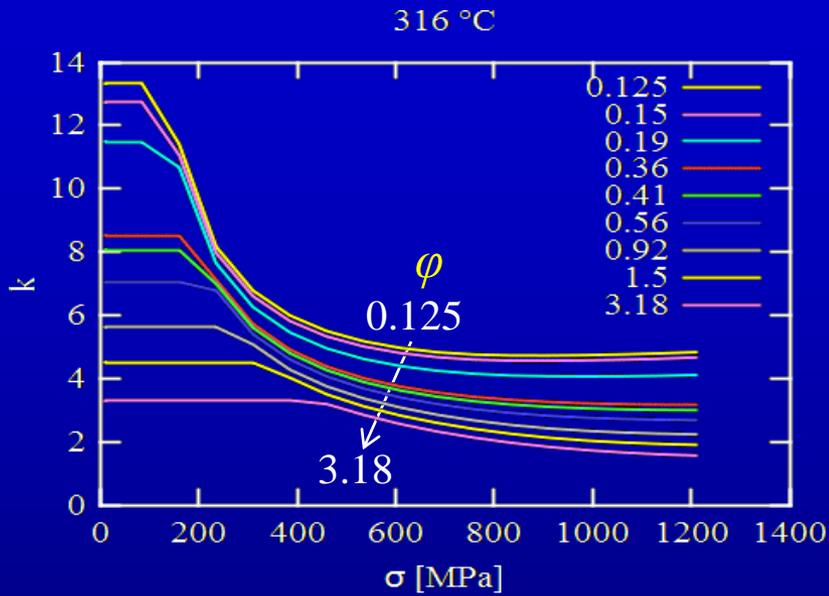
Notch tip triaxiality ratio in the 3D elastic cases -
would be 0 for plane stress and $\nu = 0.33$ for plane strain



- The elastic stress state goes from plane stress to plane strain by decreasing ϕ
- During the elastic-plastic loading, the triaxiality ratio evolves in a complex manner, with values even higher than ν in some instances.

Stress concentration factors (II)

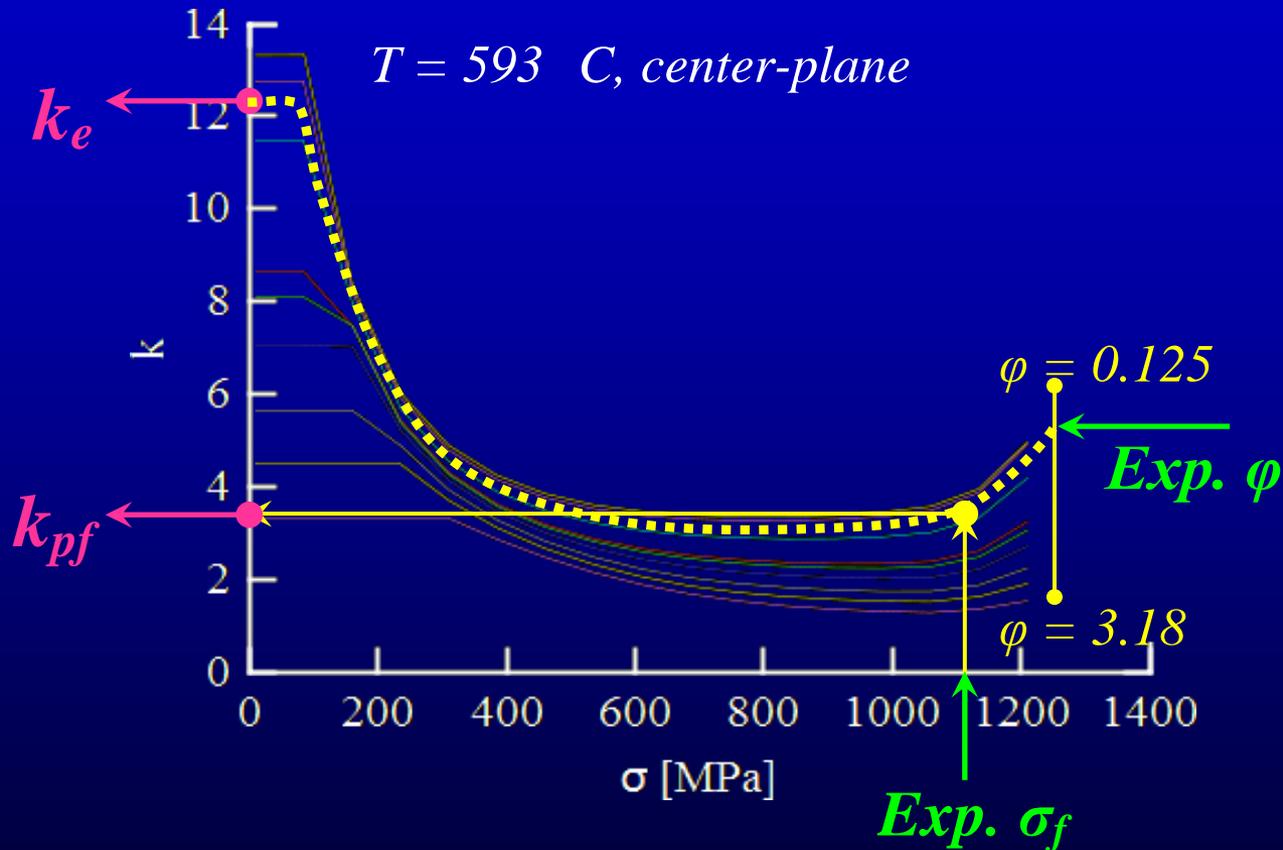
Center-plane elastic-plastic SCF, $k = \sigma_{yy} / \sigma$, vs. applied nominal stress, σ



Calculation of k_e and k_{pf}

1971: k_e from φ by the Dixon formula, $k_{pf} = UTS / \sigma_f$

2009: interpolated from FE results; k_e in respect to φ , k_{pf} in respect to φ and σ_f



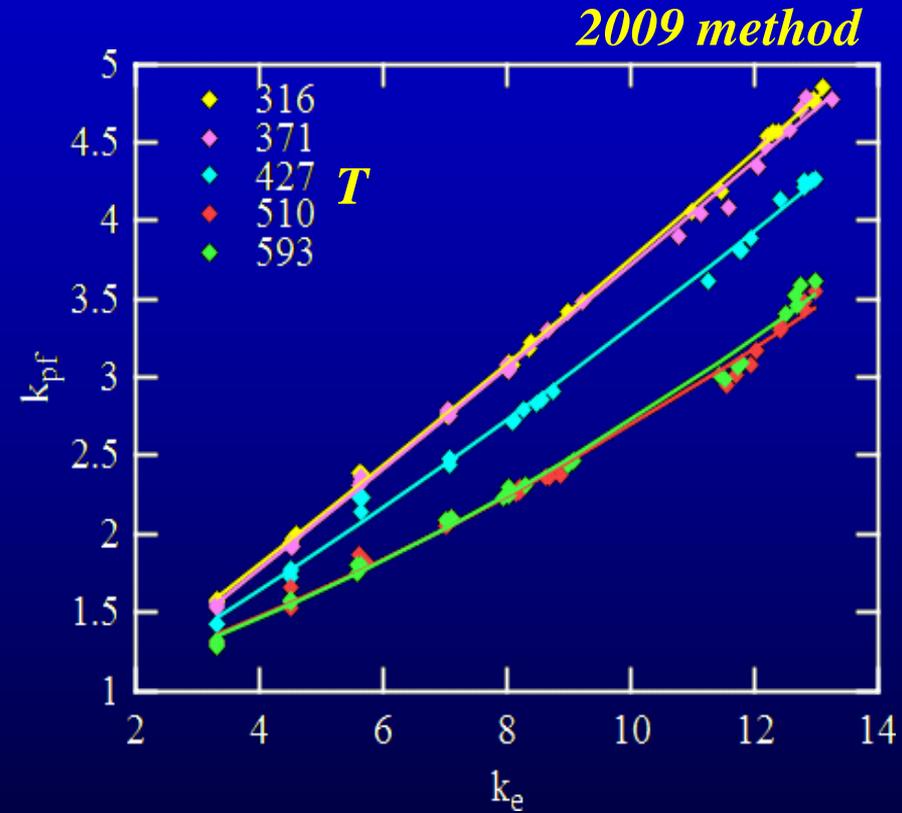
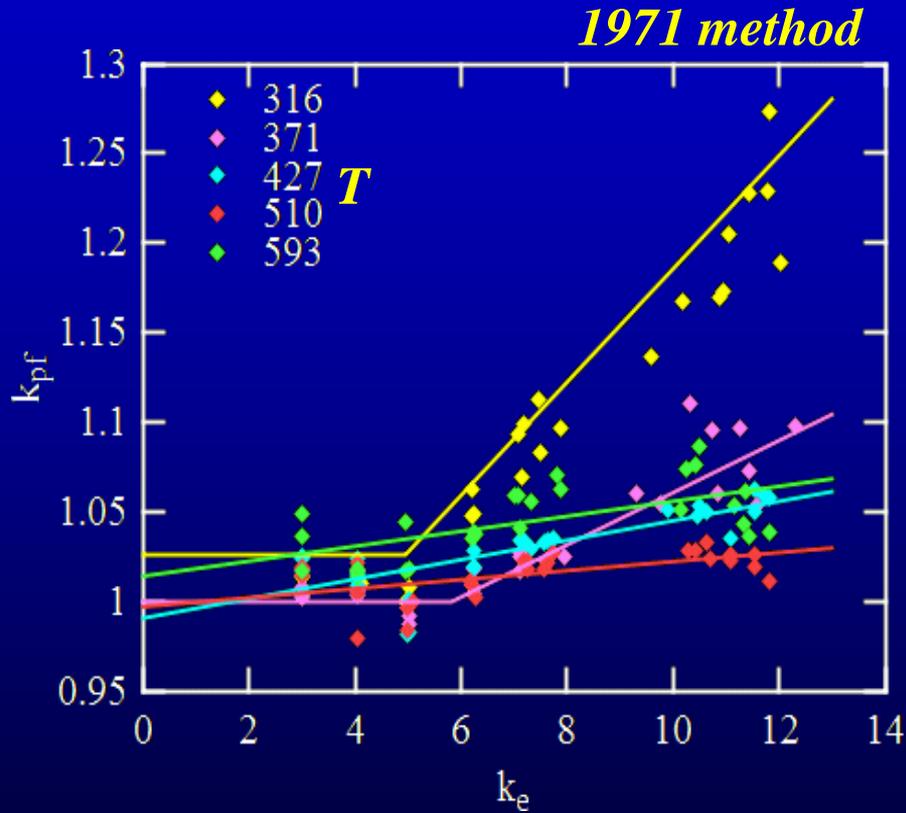
σ_f : experimental notch fracture stress

φ : experimental (initial) notch diameter

UTS : Ultimate Tensile Stress of smooth samples

K_{pf} vs. K_e

Experimental results elaborated on the basis of either the original method (left), or the present FE calculations (right).



Conclusions

1. The notch tip stress state is close to plane stress for the smaller elastic stress concentration factors (larger notch radii), and to plane strain in the opposite case, even if the thickness is constant, due to the variation of the notch radius to thickness ratio.
2. The elastic-plastic stress concentration factor at fracture, k_{pf} , is much larger than 1 (up to 4.5) and the first principal stress at the notch tip at fracture is much larger than the UTS.
3. The steel tempered at different temperatures exhibit much different behaviors; in particular, the notch sensitivity decreases sharply by increasing the tempering temperature from 371 to 510 °C.
4. The conclusions 2) and 3) above are affected by the uncertainty due to the extrapolation of the experimental stress – strain curves.

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Thank you for your attention