NEW ASPECTS OF ELASTO-PLASTIC FRACTURE MECHANICS ANALYSIS — FUEL ELEMENT CLADDING AS AN EXAMPLE

Neue Aspekte der elasto-plastischen Bruchmechanik — Bruchmechanische Analyse eines Brennstabes als Beispiel

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SUMMARY

Two problems of fracture mechanics analysis are discussed:
— stress concentration factors for three-dimensional crack configurations on cylindrical surfaces;
— generalised elasto-plastic failure criteria.

New analytical formulas have been developed describing the stress concentration factors for the crack tip on cylindrical surfaces as a function of crack-dimensions and geometry. As an example closed form solutions for cracks with finite dimensions (length and depth) in plates or cylinders of finite thickness are given. Plastic crack models from Dugdale and Irwin have been generalized under the assumption that the effective stress $M \cdot \sigma$ (nominal stress σ multiplied by a resulting stress concentration factor M) must be taken into account instead of the nominal stress σ. Then the generalized plastic crack models lead to clear relationships between elastic stress intensity factors and stress intensity factors with plastic correction.

The plastic stress intensity factors include simply defined plastic flow correction factors, $\alpha(\sigma/\bar{\sigma} \cdot M)$, ($\bar{\sigma}$-critical stress, closed to ultimate tensile stress), which are different for different plastic crack models:

$$\cos\left(\frac{\pi}{2}\frac{\sigma}{\bar{\sigma}}\cdot M\right) \quad (1)$$

$$\alpha\left(\frac{\sigma}{\bar{\sigma}}\cdot M\right) = 1-\left(\frac{\sigma}{\bar{\sigma}}\cdot M\right)^2 \quad (2)$$

$$\left(\frac{\pi}{2}\frac{\sigma}{\bar{\sigma}} M\right)^2 \Big/ \ln \sec^2\left(\frac{\pi}{2}\frac{\sigma}{\bar{\sigma}}\cdot M\right) \quad (3)$$

where (1) is valid for the generalized Dugdale-Model, (2) for the generalized Irwin-Model and (3) for a Model from Hahn, Sarrate and Rosenfield. (It is interesting to note that the generalized plastic crack models from Dugdale and Irwin are practically equivalent.) The plastic flow corrections factors (1-3) are very important for fracture failure analysis. From this analysis new universal fracture functions (depending on the plastic crack model) have been evaluated, which on one hand are independent from material behavior. On the other hand the same fracture functions can be expressed as functions of crack dimensions and of material-parameters related to fracture mechanics, e.g. C.O.D. or fracture toughness.

The general fracture functions determine the beginning of instable crack propagation and are consequently identical with a fracture failure criterion. Moreover they are valid for the total elasto-plastic behavior of materials.

All theoretical predictions are compared with other theoretical (e.g. Erdogan and Ratwani) and experimental (e.g. Hahn, Sarrate and Rosenfield) results available from literature. Their close agreement substantiates the validity of the proposed formulas.

As an example, fracture diagrams for fuel rod irradiation experiments have been set up. From such diagrams the critical stresses or critical crack dimensions can be found when the fracture mechanics parameters of a material are known (e.g. C.O.D. or fracture toughness).

Remarks are added on the applicability of the plastic flow factors in the theories of plasticity (strain-stress relationship) and of creep (as a stress dependency function in steady-state creep rate relations).

The obtained results simplify the fracture mechanics analysis and are well suited for engineering practice.