NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE STABLE CRACK GROWTH

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An article consists of three parts. In the first one the size and constraints dependence of the J–R and CTOA–curves has been demonstrated. In the second the numerical analysis of the fracture mechanics parameters during the stable crack growth (J and T^* integrals, CTOA) has been made. In the third one a new procedure of the J–R curves determination has been shown. It is based on computable size dependent quantities and size independent material parameters.

INTRODUCTION

The essence of fracture mechanics is to define the proper fracture criteria to predict the onset of crack propagation as well as the stable and unstable crack extension. It is expected that fracture criterion introduces certain parameters which would be able to characterise material from the point of view of its resistance to the crack initiation and growth. So far these expectations have been satisfied for stationary cracks and plane strain situation (thick elements). The K_{Ic}, J_{Ic}, G_{Ic} and K_{Id} are considered as material constants and are successfully used to predict the crack growth initiation. The situation is not so clear for stable and unstable crack growth that follows the onset of the crack growth. For these stages of fracture process the search for parameters that relate laboratory test specimen behaviour to structural performance has not been successfully finished. In the present article we will concentrate on stable crack growth only

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THE INFLUENCE OF SPECIMEN SIZE ON J–R AND CTOA–R CURVES

The concept of R–curves has been introduced to provide a unique tool to predict the moment of the unstable crack growth. It was expected that the R–curves would be geometry (size, constraints) independent. However, the results reported in the literature are often quite confusing. Some authors, e.g. Landes et al (1), (2) report that the J–R curves are in general geometry independent (with some exceptions). Others, e.g. Turner (3), (4) reports strong geometry dependence of the J–R curves. The comparison of the controversial results is often very difficult or impossible from various reasons. They were obtained for different materials, variety of geometrical parameters and various methodologies to measure both J–R and CTOA–curves. Therefore, an independent research program has been undertaken to test the specimen size influence on fracture resistance curves. The low hardening steel: 40HMNA (according to Polish Standards – equivalent to 4340 steel) has been selected. It was heat treated to 1100 MPa and 1287 MPa yield points and wide range of three point bend specimens with various sizes have been machined and precracked.

The tests were displacement controlled with constant displacement rate. (The MTS hydraulic machine was used.) The crack growth was measured according to the potential drop technique and compliance change technique. It should be mentioned that potential drop technique provided (for tested material and specimens) better accuracy of actual crack length measurement than compliance change technique for large crack extensions (more than 2 mm) (Neimitz et al (5)). It was also observed that compliance measured along the elastic unloading line was not identical with compliance measured along the elastic loading line, before the onset of the crack growth. If one uses initial compliance measured according to the standards may obtain „negative" crack growth at the beginning of the process. In (5) the procedure to avoid such a situation was proposed. The J–R curves were determined according to the Rice–Srawley formula (6), Ernst (7) iterative formula and Ernst modified J_M integral definition (8). Because of the lack of the space only a few J–R curves have been shown in the Figs 1, 2, 3 and 4. One may notice a strong size dependence of the R curves. The curves presented are more sensitive to the changes of initial crack length a_0/W than to the changes of relative specimen thickness. The shorter initial crack length the higher resistance to the crack growth is observed. The size dependence of modified Ernst J_M–R curves and „classical" J–R curves are the same. It is in contrast to some results reported in the literature (McCabe and Landes (9)). The CTOA–R curves were obtained using so called local and global definition: $CTOA = (\delta_{Ti}-\delta_{To})/(a_i-a_o)$ or $CTOA = (\delta_{T(i+1)}-\delta_{T(i)})/(a_{i+1}-a_i)$ where δ_{Ti} is computed crack opening displacement, indexes i and o refer to the i'th step of analysis and the onset of crack growth respectively. The CTOA–R curves are shown in the Figs 5, 6 where again the size dependence on these curves is demonstrated at least as far as the relative initial crack length is concerned. One of conclusions following from the experimental program is that the J–R and CTOA–R curves are geometry dependent for tested material.

NUMERICAL ANALYSIS OF A STABLE CRACK GROWTH

The commercial program ADINA version 6.1.4 has been utilised to compute certain fracture parameters during stable crack growth. The smallest element size was 0.05 mm. The material was assumed to follow HMH yield criterion and associated flow rule with multi linear isotropic hardening. Full Newton iteration was employed. The crack growth was modelled by the node release technique with node shifting. Experimentally registered load point displacements Δ(t) and crack lengths a(t) were used as an imput for computations. From many results obtained only a few will be included in this article. In the Fig. 7 computed J–R and T^*–R curves are presented, where T^* is Atluri – Nishioka integral (Atluri et al (10)). The shape of a J–R curve drawn according to the Ernst (7) formula much better reflects the shape of the J–R curves computed for plane strain and plane stress than the J–R curve drawn according to the Rice – Srawley definition. According to definition T^* should be path independent for small contours. Computations performed does not confirm this statement. The convergence of the T^*–R curve to a limit one has not been observed with decreasing contour of integration. The shape of a T^*–R curve has also been different then expected. For plane stress the value of T^* remains relatively constant with crack extension. This result was expected. However, for plane strain a rapid drop of the T^*–R curve is observed at the beginning of crack propagation. The results obtained may not necessarily invalidate the T^* integral as a fracture parameter. It is possible that procedures of interpolation during the remeshing process adopted within ADINA affect the results.

The CTOA was measured directly from the shape of the near tip crack region (Fig. 8). The shape of the R–curves and the value of the CTOAs are similar to those measured experimentally.

A NEW POINT OF VIEW ON J–R CURVE DETERMINATION

The concept of the J–R curve has a good physical interpretation if the stable crack growth is considered as a sequence of equilibrium states. However, it must be pointed out that the J integral can only be interpreted as a global parameter representing the energy stored and dissipated during the stable crack growth. It is not path independent and it is not an amplitude of the singular HRR field when crack is growing. In general the J–R curve is determined by measuring the area under the force (P) – displacement (Δ) curve. Thus, it must be geometry depended and it reflects not only the property of material but the properties of the whole system. Plastic dissipation depends on the geometry and size of the specimen as well as mechanism of fracture does. Following Turner (4) and Neimitz (11) arguments the crack growth equation can be written in terms of J integral as follows:

$$J - J_{el} = J_{pl} = D \quad \text{.......} (1)$$

where D is dissipation function. According to (11) D should be computed from the analysis of dissipative processes and should contain computable parameters depending on geometry and material parameters independent of size and geometry of specimen. It has been assumed here that two dissipative processes dominate during the crack propagation process: plastic dissipation and process zone creation (voids, microcracks). Thus, it was assumed as a first approximation that the energy dissipated by plastic deformation is proportional to a product of ξV where ξ is specific energy of plastic deformation, V is the volume of material where the plastic deformation takes place. Similarly the amount of energy dissipated within the process zone is equal to a product of $\eta \Delta A$ when η is specific energy of process zone formation and ΔA is extension of the crack surface. ΔA can be taken from experiment, V can be computed with the help of finite element method and material parameters ξ and η can be computed from a selected J–R curve for a tested material solving two equations:

$$\begin{aligned} J_{pl(1)} &= V_{(1)}\xi + \Delta A_{(1)}\eta \\ J_{pl(2)} &= V_{(2)}\xi + \Delta A_{(2)}\eta \end{aligned} \quad \text{.......} (2)$$

Subscripts 1 and 2 refer to a two arbitrary points along the J–R curve. The linear form of Eqs (2) was assumed for a tested material because of its weak strain hardening. If the quantities ξ and η computed from (2) are material parameters one should „reconstruct" the J–R curves for other geometries and sizes provided $V_{(i)}$ and $\Delta A_{(i)}$ are known. It was done for a tested material and three different specimen sizes where the pairs of ξ=0.81 N/m^4, η=14.679 N/m^3 for plane strain and of ξ=1.279 N/m^4, η=24.074 N/m^3 for plane stress provided a tool to obtain the J–R curves for different specimens in agreement with experiment. Detailed procedure of computation will be published elsewhere. However, it should be mentioned that the linear form of Eqs (2), although very simple, makes parameters ξ and η very sensitive to changes of other quantities (J_{pl}, V, ΔA). Thus they have to be evaluated very carefully, including correction of the crack extension Δa due to the shear lips formation. Results obtained with the help of the presented model are promising and this direction of research will be continued.

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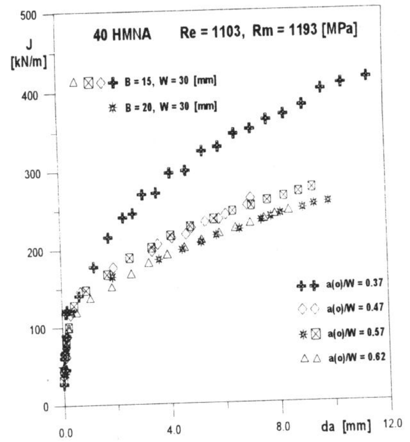

Figure 1 J-R curves according to Rice Srawley formula.

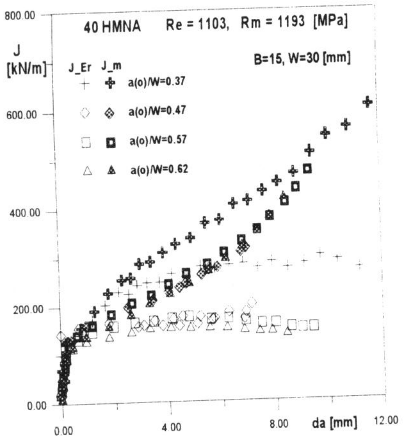

Figure 2 J-R curves according to Ernst formulas.

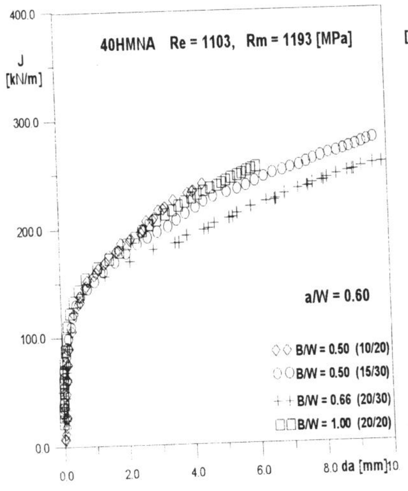

Figure 3 J-R curves according to Rice -Srawley formula.

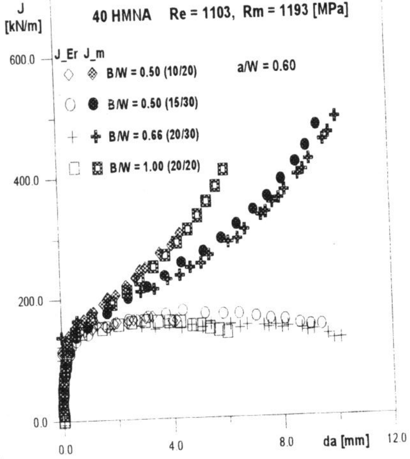

Figure 4 J-R curves according to Ernst formulas.

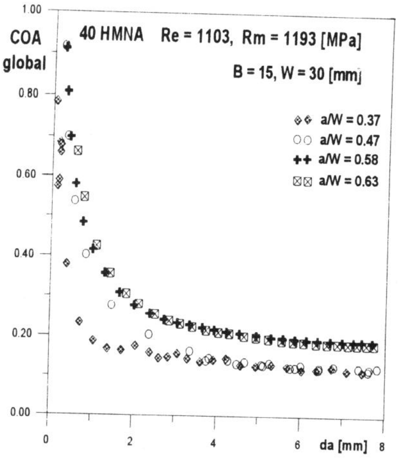

Figure 5 CTOA-R curves.

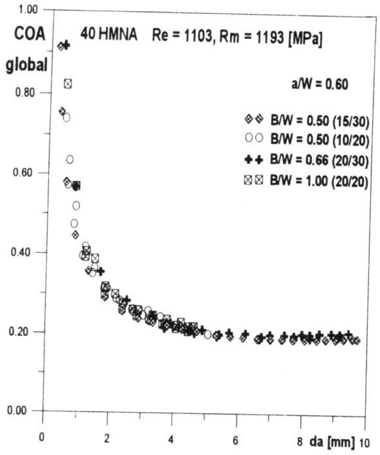

Figure 6 CTOA-R curves.

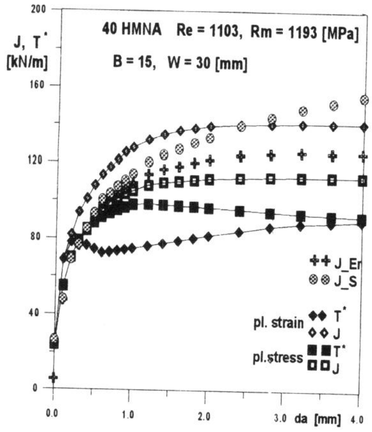

Figure 7 J-R and T*-R curves.

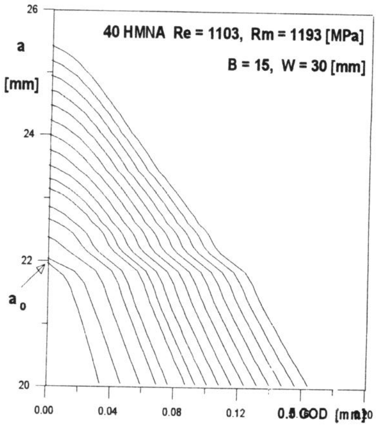

Figure 8 Crack profiles and COD