Study of Relation between Lifetime Levels at the Stages of Fracture Nucleation and Propagation under Cyclic Loading

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As may be inferred from pressure vessel service experience and test results under cyclic loading there exists considerable difference in number of cycles prior to macrocracking under low cycle loading of smooth specimens and full-scale structural elements. Therefore, cyclic loading resistance design of a structure usually includes 20-fold lifetime and 2-fold strain safety factors in relation to a fatigue curve obtained for smooth specimens. In the present paper an attempt has been made to analyse it starting from the assumption that massive sections of large products have always initial fabrication defects which may be the sites of fatigue damage nucleation. In this connection,number of cycles to fatigue crack initiation sharply decreases in full-scale structures, and propagation of these cracks is the main process which governs structure lifetime.

In order to check the applicability of the above suggestion a correlation was made between test results under cyclic loading in elastic-plastic region for specimens containing fabrication defects and generallized data of pressure vessel fatigue tests under cyclic loading as given in a paper by Ruiz/2/ (see Fig.1). The specimens were made of low-carbon steel (U.T.S = 40kg/mm^2) and low-alloy steel(U.T.S.=70kg/mm^2), and of their welded joints as well. The defect in the middle of the gauge length was of an internal slag inclusion type. Maximum defect size values lay between 1.0 and 3.0 mm. Specimens were subjected to the given level of deformation in symmetric cycle which most closely corresponded to metal loading conditions in stress concentration zones. During testing a moment of crack appearance on the lateral surface of the specimen was noted. It was assumed to be the moment of fatigue crack initiation.

Figure 1a illustrates data scatter ranges for pressure vessel tests as it is shown in paper /1/. It should be emphasized that pressure vessel lifetime is determined from the moment of fatigue crack initiation. In the same figure there are points corresponding to test results of specimens with accidental defects. A good correlation between specimen and vessel test results provides a support to the validity of the assumption mentioned that in pressure vessels tested failure is generally nucleated from the available fabrication defects. This can mainly allow for the reduction of full-scale structure lifetime as compared to small smooth specimens.

The results obtained permitted to suggest a calculation diagram to evaluate fatigue crack growth under loading of material in elastic-plastic region. Paris's relation used in such a purpose /2/

$$\frac{da}{dN} = C(\Delta K)^m \qquad (1)$$

where $\frac{da}{dN}$ - fatigue crack growth rate;

ΔK - stress intensity factor range;

m and C - material constants

can be applied only in the case of material loading in elastic region since the calculation of ΔK value on the basis of the well known formula is impracticable when loading the material beyond this range. An approximate method of estimating fatigue crack propagation in elastic-plastic region of loading utilizing the relation(1) is basen on introducing a fictitious value for stress intensity factor ranges ΔK_f , the latter being equal to

$\alpha \Delta K$ (2)

where α - factor which implies a specific character of fatigue crack propagation under elastic-plastic strain;

ΔK - stress intensity factor range calculated using formulas of linear mechanics.

In this case the stress value is assumed to be equal to allowable amplitude of alternating stress intensity $S_a = E\varepsilon_a$ where E-modulus of elasticity, ε_a -strain amplitude. In order to identify α factor test results for defective specimens have been used for which depending on fracture surface schematic presentation of fatigue crack front in defective region can be given as concentric circumference down to the crack exit on to the specimen lateral surface(see Fig.1b). This is the case when lifetime required for crack propagation can be evaluated using the formula (4)

$$N = \frac{(\pi)^{m/2}}{(2\alpha S_a)^m C} \int_{a_0}^{a_K} \frac{da}{a^{m/2}} \qquad (4)$$

If the initiation of the crack from a defect is assumed to occur at the first cycle of specimen loading, then α factor relation may be obtained starting from the formula(4) by means of recalculation at N=N*, where N* is a number of cycles to crack exit on the lateral surface of the specimen.In calculations stated above C and m constant values were found experimentally by testing specimens of the materials under investigation in elastic region. The results of these calculations given in Fig.1b show that α factor values for the materials tested with 10% data scatter concentrate near the curve 1 which is offered to be used in calculation assessment of fatigue crack growth rate under elastic-plastic loading.

The analysis made on the basis of the calculation technique suggested has promoted a physical interpretation of Ruiz curve(Fig.2). This curve corresponds to lifetime required for fatigue curve growth from the initial size adequate to the acceptance level in the pressure vessel quality inspection code, to the magnitute at which the growth can be noted by non-destructive testing. In a particular case this may correspond to a double accidental defect size.

References

1. Ruiz C. The Engineer,vol.224,Nr 5818,July,28, 1967.
2. Paris et al. Technical mechanics, Nr 4, 1963.

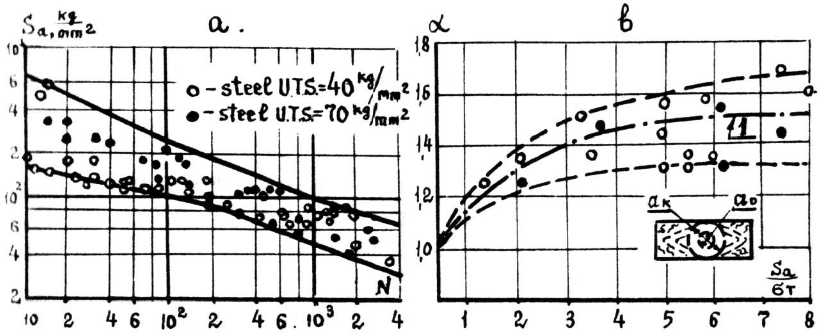

Fig.1. Test results of specimens with accidental defects.

a/ comparison with Ruiz's data.
b/ dependence of α factor on S_a/σ_Y relation.

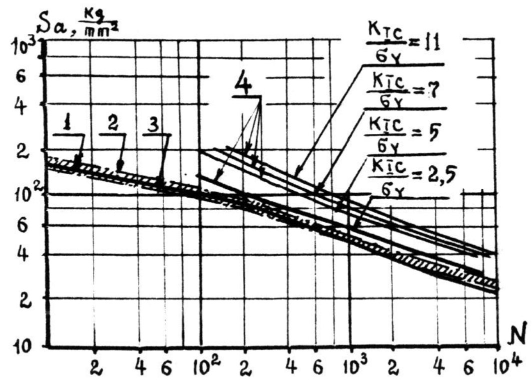

Fig. 2. Estimation of pressure vessel endurance at the stage of fatigue crack propagation.

1. Low bound of scatter band of Ruiz's experimental data.
2, 3. Pressure vessel endurance estimated by doubling defect size on the account of fatigue crack propagation.
4. Pressure vessel endurance before fatigue crack propagation,imitating brittle fracture.