The Materials Low Cycle Fatigue Evaluation with Regard to the Stress Concentration Factor

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Low cycle fatigue strength of structures is governed by the metal behaviour in stress concentration regions. The stress level in these regions can considerably exceed the material yield strength. According to modern method of estimation structure endurance is identified using the fatigue crack initiation conditions on the basis of Coffin-Langer's equation, applicability of which has been experimentally supported by testing materials of different strength level. As it is shown in paper /1/ for the approximate calculations the following equation may be used:

$$S_a = \frac{E}{4 \cdot \sqrt{N}} \cdot \ln \frac{100}{100-\psi} + \frac{\sigma_u}{2} \quad \ldots\ldots (1)$$

where $S_a = e_a E$ - allowable amplitude of alternating stress intensity;

e_a - total strain amplitude;

E - modulus of elasticity;

N - number of cycles to crack initiation;

ψ - reduction of area;

σ_u - ultimate tensile strength.

S_a value in the most stressed region of a structure can be obtained if the strain concentration factors are known:

$$K_{\varepsilon_{max}} = S_a / \sigma_{nom} \quad \ldots\ldots (2)$$

where σ_{nom} - calculated mean stress intensity.

These factor values characterize design quality of the most heavily stressed units in typical structures. The estimated and experimental data obtained by different investigators has shown that for pressure vessels the values of the strain concentration factor vary in the range 2.5 to 5 depending on the type of the structure.

As the trend to use high strength materials for pressure vessels becomes increasingly pronounced, it is of particular interest to analyse structure endurance as a function of design quality and tensile properties of the materials used, starting from present standards (ASME Code, for example) and holding true the equation (1). For this purpose on the basis of the equation (1) and taking into account the relationship (2) a nomograph for fracture conditions of pressure vessels versus the material properties and $K_{\varepsilon\, max}$ values was constructed. In this case the assumption was made that for vessels $\sigma_{nom} = \frac{\sigma_u}{2.6}$ (3). The relationships for $N = 5 \cdot 10^3$ cycles given in Fig.1 were plotted taking into account safety factors 20 suggested by ASME Code, that is the most typical lifetime for power units. Figure 1 shows also a scatter band of mechanical properties for various structural materials. Separate points in the band corresponding to mechanical properties of certain best known materials are shown in this figure. It is evident from Fig. 1 that to retain given structure endurance leaving invariable design quality of a vessel, it is important by increasing material strength to raise its ductility. However, in reality material strength is accompanied as a rule by a certain drop of ductility. In this connection, in structures with U.T.S. = 40-50 kg/mm^2 the required endurance is provided in practice even for

most unfavourable values of $K_{\varepsilon\, max}$. When increasing the strength level of the material used with accompaning mean stress level raise, it is necessary to decrease $K_{\varepsilon\, max}$ value to maintain structure endurance. So if the number of cycles $5 \cdot 10^3$ then for production of the most heavily stressed structure units $K_{\varepsilon\, max}$ should be 3.5 for materials having U.T.S.> 70 kg/mm^2 and 3 to 3.2 for materials having U.T.S.= 90-100 kg/mm^2.

The considerations mentioned above are based on purely formal analysis. The drawback of the latter is that the assumed safety factor 20 includes all integrated factors which are effective in structure production and operation. The consideration of pressure vessel fractures has shown that metal fabrication defects or various surface imperfections in the most heavily stressed units constitute the main reason of this phenomenon. Taking into consideration this fact in the present paper it was attempted to look over the requirements imposed upon the material in connection with its local production or metallurgical imperfections. Some relations are given by Langer /2/ who evaluated the correlation of structural material endurance and crack size for different strain concentration factors on the basis of Peterson's hypothesis. Such analysis is applied to fatigue when metal is in elastic region. It is known that the material in stress concentration zones is in elastic-plastic region, therefore the analysis given above needs refinement. For this purpose defective specimens were tested and the values of effective strain concentration factors (k_f) were estimated for various types of defects. Comparison between theoretical and experimental values of k_f factor has shown a good correlation of results (Fig.2). In materials with crack and pore type defects there is practically no discrepancy and in those having defects of a less definite form (slag inclusion) some discrepancy can be observed.The majority of experimental data corresponding to a slag inclusion approach the curve plotted for the crack. Therefore prior to obtaining statistical knowledge concerning the most typical slag inclusion form in a structure it is advantageous to present any defect in the form of a crack. Such assumption gives some higher k_f values for slag inclusions. Thus fabrication metallurgical and other defects should be considered as an initial crack with a typical size equals to the maximum defect size. Then the nomograph shown in Fig.1 can be somewhat modified. A similar nomograph is given in Fig.3 in $\sigma_u - \psi$ coordinates with different structural strain concentration factors and a technological concentrator through a defect is additionally taken into account. So the use of materials with U.T.S.>40 kg/mm^2 requires the improvement of pressure vessel design quality and the decrease of acceptance levels of defects.But for materials with U.T.S. >60 kg/mm^2 without this improvement we cannot avoid low cycle fatigue crack appearance . In this case fatigue crack propagation is taken into account.

References:
1. Langer B.F. Journal of Basic Engineering for Industry. Transaction of the ASME,September,3,1962.
2. Langer B.F. et al. Journal of Engineering and Power. Transaction of ASME, Ser.A,4,1964.

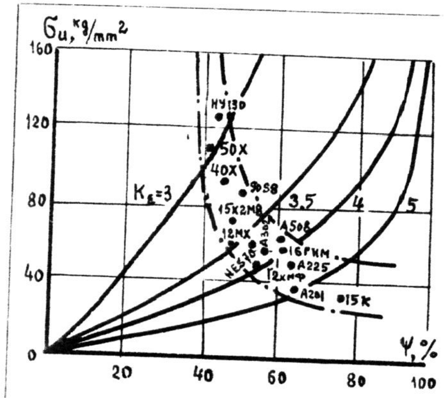

Fig.1 Nomograph of pressure vessel fracture conditions.

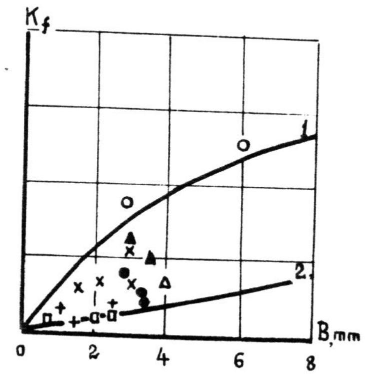

Fig.2. Correlation of estimated and experimental k_f values for the material with U.T.S. = 40 kg/mm^2.

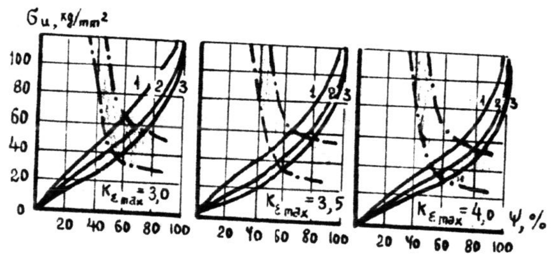

Fig.3. The conditions of fatigue fracture appearance in pressure vessels by $N=5 \cdot 10^3$ cycles versus design quality of stress concentration regions, containing 2,4, 6 mm cracks.