FATIGUE LIFE PREDICTION OF WELDED STRUCTURES BASED ON COMBINATION OF STRAIN AND STRESS APPROACHES

L.K. STEINZEIG

Institute of Problems of Mechanical Engineering,
Russian Academy of Sciences
V.O. Bolshoy Pr., 61, 199178, St. Petersburg, Russia

K.P. MANDJULA

Mechanical Engineering Department, State Technical University,
Polytechnicheskaya, 29, 195251, St. Petersburg, Russia

ABSTRACT

In order to improve welds design codes the approach which combines strain and stress (S-N) fatigue failure criteria is developed. Fatigue life of a structure component is regarded as a process containing two stages. The first stage suggested as a process of residual weld stresses interaction with service loading stresses at varying cyclic reaction of heat-affected zone (HAZ) metal. This process is concentrated in a small region of strain elevation at weld root. The completion of this stage is characterized by final strain redistribution and stationary process of deformation, which determines real strain-stress fields of weldments for the second stage. The local stress-strain cyclic fields at a weld root are obtained using the stress and strain concentration factors along with relative stress and strain gradients.
The method efficiency has been verified by experimental data for cruciform weldments fabricated by electric arc welding from 10XCHD low alloy steel.

KEYWORDS: weldments, fatigue life prediction, heat-affected zone simulation, nonstationary process of deformation

The initiation of fracture in sound and rationally designed weldments occurs usually at the toe of a welded joint. Also, the fatigue life of a welded structure within the crack initiation period is determined by fatigue behaviour of a small volume of metal. This volume is sided, in a field of maximal surface strains or/and stresses and usually coincide with grain-coarsened domain of HAZ-metal. This part of HAZ is called the subject-of-analysis zone (hereafter SAZ) .
The present method of fatigue life prediction is based on comparison of loading condition of smooth specimens with SAZ-metal simulated properties and of SAZ-metal of weld joint under examination. It is suggested that the accumulation of fatigue damage and the early period of fracture consists of two stages.

The first stage is approached using a cyclic straining routine viewpoint. This emphasizes the critical role of plastic strain in damage accumulation, and identifies the important phenomena resulting from inelastic stress-strain behaviour such as mechanical hysteresis, cyclic hardening and softening, cycle-dependent creep and stress relaxation. One of the results of these processes is the redistribution of stress-strain fields and therefore changes of local stress ratio in SAZ-metal. At this stage the damage is evaluated on the basis of a reversal-by-reversal stress-strain analysis of a load history using the local accumulated plastic and elastic strain range as a failure parameter. It is assumed that the damage is equal to sum of quasi-stationary and low-cycle components.

The second stage of the failure is controlled by constant strain-stress relation and local stress ratio. It is assumed that the rest of the damage is determined by the low- or high-cycle component. It depends on existing up the moment SAZ-metal properties and its loading after the completion of nonstationary process of deformation.

Most likely that the weld will fracture in case the SAZ-metal will attains the fatigue macrocrack. Accordingly, the damage summation towards the unity identifies the weld failure by the following equation

$$d = d1 + d2 + d3 , \qquad (1)$$

where $d1 = e^{saz}_{pk} / e^{saz}_{f}$ - quasi-statically damage;

$e_{pk} = e^{saz}_{p0} + \sum_{1}^{k} \Delta\varepsilon_{pi}$ - one-sided accumulated strain in SAZ-metal in continuation of k-reversals of local nonstationary process;

$e_{p0} = e_m + e_a + e_{res} - \sigma_p / E$ - plastic strain due to zero reversal; e_m , e_a - mean strain average and strain amplitude accordingly; e_{res} - residual welding strain; E, σ_p - elasticity modulus and proportionality limit accordingly;

e_f - critical strain of SAZ-metal;

$D2 = \sum_{1}^{k} \varepsilon^{saz}_{pi} / (\sum_{1}^{k} \varepsilon^{saz}_{pi} + \varepsilon^{saz}_{pk}(2N_N - k)$ - low cycle damage;

ε^{saz}_{pi}, ε^{saz}_{pk} - plastic strain of "i" and of "k"-reversals of SAZ-metal accordingly; $2N_N$ - fatigue life of welded joint, in reversals;
k - number of nonstationary strain reversals ;

$D3 = (2N_N - k)/(2N_k)$ - high-cycle damage;

$2N_k$ - fatigue life of SAZ-metal, in reversals.

Fig.1 illustrates the cyclic strain-stress curves for cyclic softening SAZ-metal, details which were discussed above.

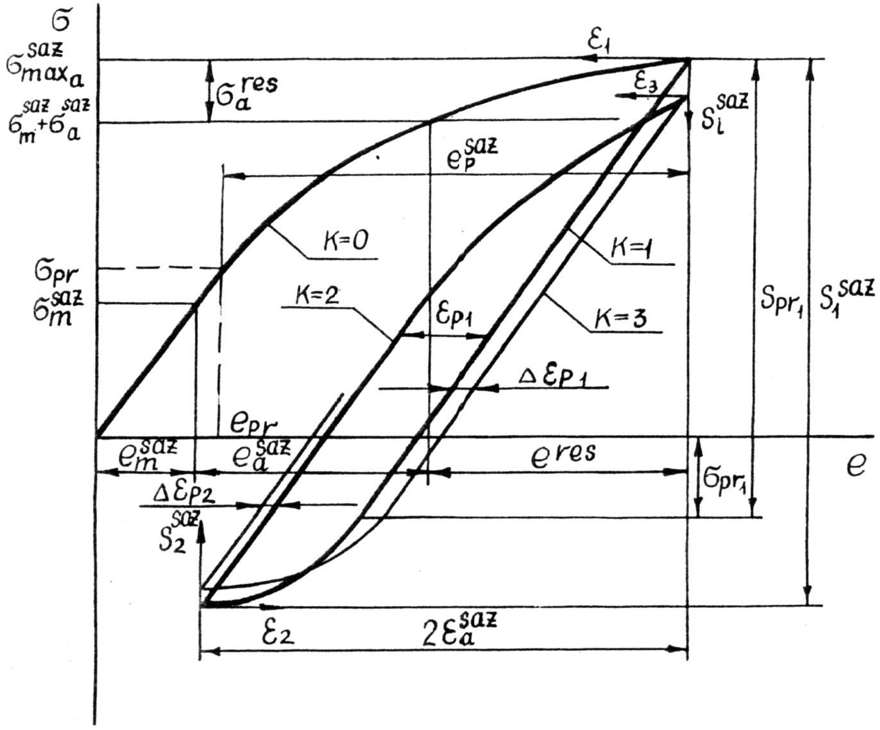

Fig.1. The cyclic strain-stress curves for cyclic softening SAZ-metal of a weldment

After all, the equation (1) will have the following form

$$e^{saz}_{pk}/e^{saz}_{f}+\sum_{1}^{k}\varepsilon^{saz}_{pi}/(\sum_{1}^{k} \varepsilon^{saz}_{pi} + \varepsilon^{saz}_{pk}(2N_N - k)) + (2N_N-k)/(2N_k)=1. \qquad (2)$$

The elements of the equation (1) describe different parts of damage of SAZ-metal, but sum of these damages reflexes accumulation of damages of weldment as a whole. Practically, the equation (2) enables the estimating of weldment fatigue life N_N under applied nominal stress σ_{RN} . However, this procedure requires additional information about properties and local strain-stress fields in SAZ-metal. To determine the number of internally nonstationary k-reversals the following expression may be used

$$\mid \varepsilon_{p1}^{saz} - \varepsilon_{1-2}^{saz} \mid \leqslant U^{saz} \quad , \qquad (3)$$

where U^{saz}-the lower boundary of endurance limit dispersion for SAZ-metal.

Plastic strain in SAZ-metal of weldment depends on strain concentration factor K_ε, nominal stress amplitude σ_a, cyclic proportionality limit S_p^{saz} and may be determined by the following relation

$$\varepsilon_{p1}^{saz} = (2K_\varepsilon \sigma_a - S_{p1}^{saz}) / E \quad . \qquad (4)$$

The fatigue life N_k of SAZ-metal depends on the local strain level in k-reversal. If strain ε_{pk}^{saz} is greater than ε_M^{saz}, according to boundary point between low- and high-cycle of fatigue curve regions (see Fig.2), then the fatigue life N_k is determined by modified Coffin's equation, written in the form

$$N_k = (\varphi_\varepsilon C_p / \varepsilon_{pk}^{saz})^{1/m\,\varepsilon} \quad , \qquad (5)$$

where φ_ε - strain similarity factor between strain states of weldment's SAZ-metal and smooth specimen of simulated SAZ-metal ; C_p - constant of Coffin's equation ; m_ε - strain exponent of fatigue curve of specimens .

In case the level ε_{pk}^{saz} in k-reversal is less than or equal ε_m^{saz} the fatigue life N_k is determined by modified Wohler's, which can be written in the form

$$N_k = N_G \, (\varphi_\sigma \, \sigma_R^d \; / \; \sigma_{Rk}^{saz} \,)^{m\,\sigma} \quad , \qquad (6)$$

where φ_σ - stress similarity factor between stress states of weldment's SAZ-metal and smooth specimen of simulated SAZ-metal; σ_R^d - endurance limit of simulated smooth specimens according to N_G cycles; σ_{Rk}^{saz} - maximal local stress in weldment's SAZ-metal for k-reversal of loading ;m_σ - stress exponent of fatigue curve of simulated specimens.

The grain coarsened region of HAZ (SAZ-metal) was reproduced by simulating of weld thermal cycle in a smooth specimens which ones were large enough for the traditional methods of mechanical, strain- and load-controlled fatigue test. As the result of simulation the homogeneous structure has been produced in the gage length about 30 mm . It was according to investigate the zone of welded joints. The properties of the zone were verified by metallographic, radiographic analyses and hardness study. The result of these studies were performed on the simulated SAZ specimens and compared with the actual weld SAZ-metal.

Parameters m_ε , C_p , m_σ , σ_R were determined in low- and high-cycle tests of simulated smooth specimens accordingly.

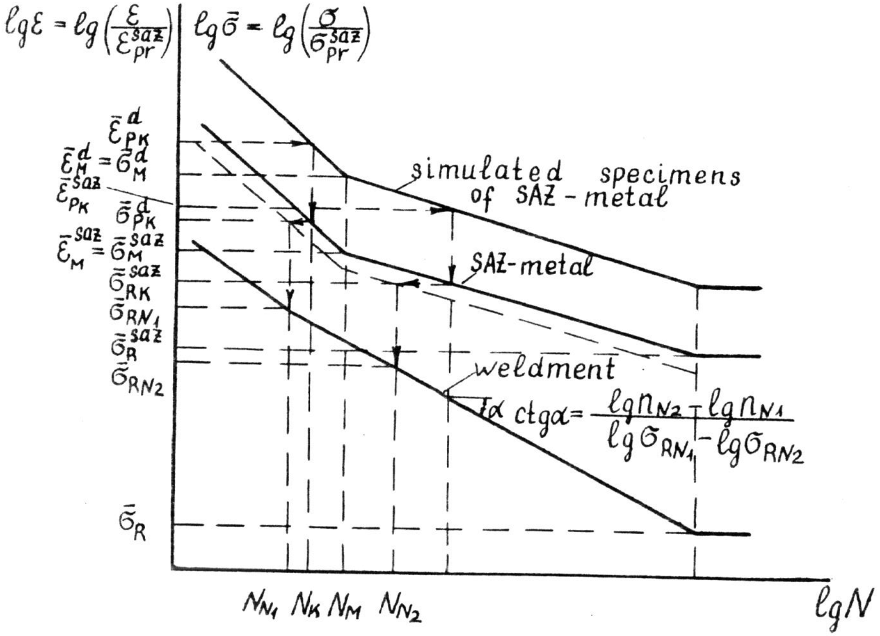

Fig.2. The schematic sequence of weldment's fatigue life estimation

The similarity factors φ_ε and φ_σ are accounting for scale effect influence in fatigue. To consider the role of this effect using the Weibull's weakest-element hypothesis were obtained the following relations:

$$\varphi_\varepsilon = (V_\varepsilon^d \,/\, V_\varepsilon^{saz})^{1/\beta_\varepsilon} \quad (7); \qquad \varphi_\sigma = (V_\sigma^d \,/ V_\sigma^{saz})^{1/\beta_\sigma} \quad (8),$$

where V_ε^d, V_σ^d, V_ε^{saz}, V_σ^{saz} - fatigue damage affected volumes of simulated specimen's metal and weldment's SAZ-metal, which sustain cyclic strain ε_{pk}^{saz} and stress σ_R^{saz} of equivalent levels in specimen and SAZ-metal;

β_ε , β_σ - exponents of Weibull's distribution.

The fatigue damage affected volume in low-cycle region is a volume of metal where the strains are above the yield strain of SAZ-metal ε_y^{saz}.

The fatigue damage affected volume in high-cycle region is a volume of metal where the stresses are above the lower boundary of endurance limit dispersion for SAZ- metal U^{saz}.

The details of strain, stress similarity factors, the affected volumes determ as well as loading condition of a specimen shown in Fig.3 and Fig.4.

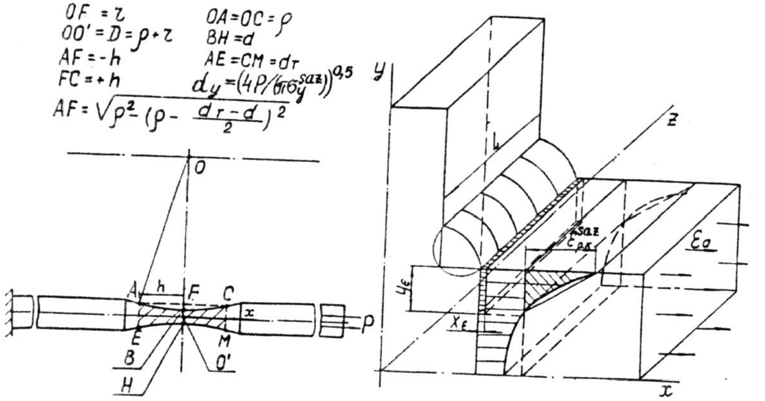

Fig.3. The determination of strain similarity factor for smooth specimens and welds

The relations for estimation strain and stress similarity factors have the following forms:

$$\varphi_\varepsilon = \{ \frac{\{2\pi h[\ (D^2 + \rho^2) - h^2/3] - 4\pi D[0.5\ h^2(\rho^2 - h^2)^{0.5}}{\varepsilon_{pk}^{saz}\ E\ L} +$$

$$+ \frac{0.5\rho^2 \arcsin(h/\rho)\ \}\ G_\varepsilon\ K_\varepsilon\ \sigma_R}{\varepsilon_{pk}^{saz}\ E\ L} \}^{1/\beta_\varepsilon} \qquad (9)$$

$$\varphi_\sigma = \{ \frac{\pi d^2[1 - (u^{saz}/d)^2]}{4y_{\sigma u}\ L} \}^{1/\beta_\sigma} \qquad (10)$$

where $\bar{G}_\varepsilon = (\varepsilon_{max}^{saz} - \varepsilon_y)/y_\varepsilon/\varepsilon_{max}^{saz} = \varepsilon_{pk}^{saz}/(K_\varepsilon \varepsilon_a y_\varepsilon)$ - relative strain gradient.

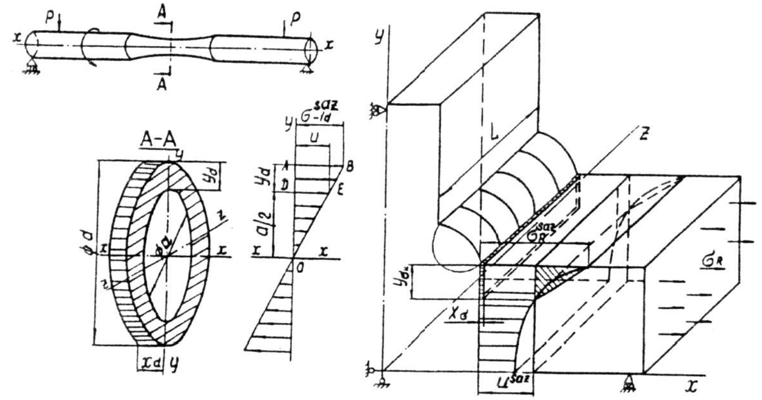

Fig.4. The determination of stress similarity factor for smooth specimens and welds

In such a manner, the fatigue life of SAZ- metal is determined by equation (5) or (6). It depends on correlation of strains ε_{pk}^{saz} and ε_M^{saz} .

Then, to estimate the fatigue life N_N one has to find the solution of the equation (2) accounting for information on local properties and strain-stress conditions in SAZ-metal of a weldment. To realize this is taken a provisional nominal stress $S = \sigma_R$. The calculation at several nominal stress values gives possibility to obtain the design calculational S-N curve. Schematically this process is shown in Fig.2.

In this way, along with the appropriate experimental data the present method based on combination of strain and stress approaches allows to obtain the design S-N curves for weldments with arbitrary proportions and geometries.

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