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PRESSURE VESSEL STRENGTH ANALYSIS BY THERMAL SHOCK

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Under pressure vessels operating conditions sharp cooling may occur due to various emergency situations and necessity of heat removal from inner components. The resulting tensile thermal stresses (even at the first instant of time) exceed the material yield strength. With regard to thick-section nuclear vessels much consideration should be given to the estimation of brittle fracture resistance.

This paper describes the main principles of thick-walled pressure vessel design in reference to brittle fracture resistance with consideration for non-uniform temperature and stress distribution over the wall thickness.

The design problem is to determine such structure stress conditions when stable existence of possible cracks in metal is provided. The damage of brittle fracture by isothermal loading grows with crack depth increase, but in the case of non-isothermal loading this relation may be broken down. The reason lies in the fact of the combined action of two opposite factors. On the one hand as the crack depth increases the metal stress concentration at the crack tip is also increased. On the other hand as the crack depth increases its tip is found in the higher temperature region and metal brittle fracture initiation resistance grows. In this case the following equation may be used to assess structure brittle fracture resistance

$$n_\sigma = \frac{K_{IC}}{K_I} \qquad (1)$$

where n_σ is in principle a safety factor expressed in the terms of fracture mechanics.

With reasonable thermal stress distribution (for the most dangerous surface cracks) K_I can be found from the well known equation (1).

$$K_I = f\left(\frac{a}{B}\right) \frac{2\sqrt{a}}{\sqrt{\pi}} \int_0^a \frac{\sigma(x)}{\sqrt{a^2-x^2}}\, dx \qquad (2)$$

where x is crack depth coordinate, $\sigma(x)$ is the function of thermal stress distribution.

The function $\sigma(x)$ takes into account the crack asymmetric position and shape and at the first approximation may be determined on the basis of comparing of the existing surface semielliptical cracks estimation in uniform tensile stress field and the analysis results in accordance with the equation (2).

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From the practical standpoint it is useful to estimate K_I in tensile stress region. For the sake of simplicity this zone stress distribution may be treated with the linear function as to find for the stress intensity factor a rather simple expression

$$K_I = f\left(\frac{a}{B}\right)\sqrt{\pi a}\left(1 - 0.64\,\frac{a}{\ell}\right)\sigma_o \qquad (3)$$

where ℓ is tensile stress region value, σ_o is vessel inner surface thermal stress.

The K_{IC} value, characterizing brittle fracture initiation resistance, may be defined from the estimation of wall thickness temperature distribution and from the experimental data of pressure vessel material plain-strain fracture toughness temperature dependence.

By structure strength estimation in the absence of K_{IC} temperature dependence data advantages can be gained from generalized brittle fracture resistance relationships which represent a more conservative bending of experimental results. For pearlitic steels (σ_y = 600MN/m^2) the analytical expression of such bending is

$$\frac{K_{IC}}{\sigma_y} = \frac{300}{60-T_z} \qquad (4)$$

where T_z is relative loading temperature

$$T_z = T - T_D .$$

The relation $n_\sigma = \frac{K_{IC}}{K_I}$ depends on the following parameters

$$n_\sigma = f[a,t,B,T_o(T_D-T_\ell)] \qquad (5)$$

where T_o is pressure vessel wall temperature before cooling, T_ℓ is cooling liquid temperature.

This relation enables to calculate n_σ for any instant of time as the function of crack depth. The calculation results for two various values of $\Delta T_D = T_D - T_\ell$ are given in Figure 1a and 1b.

The calculation was performed for 140 mm wall thickness pressure vessel being cooled from T_o = 573°K to T_ℓ = 313°K. As illustrated in Figure 1a and 1b, n_σ crack depth dependence is extremal. Minimum $(n_\sigma)_{min}$ values define the most dangerous critical crack sizes at any instant of time. It should be noted that crack sizes are rather small (6 - 12 mm). These crack sizes may comply with the sizes of possible defects in thick-walled pressure vessels.

From the above equations one can see that $n_\sigma = f(a,t)$ function has extremum not only in parameter a but also in t. It enables to find full extremum and define the value of $[(n_\sigma)_{min}]_{min}$ for each case on the basis of relation between $(n_\sigma)_{min}$ and time from the cooling moment (Figure 2).

Brittle fracture-safe assurance may be predicted as

$$[(n\sigma)_{min}]_{min} > 1 \qquad (6)$$

when the structure operates in accordance with this equation, its stress levels and temperature fields are not enough to initiate brittle fracture at any initial crack sizes.

The applied estimation approach provides the possibility of definition of acceptable thick-walled pressure vessel loadings by sharp cooling or other nonstationary conditions.

On the basis of the given analysis procedures the requirements to pressure vessel materials may be determined with the maximum brittleness transition temperature.

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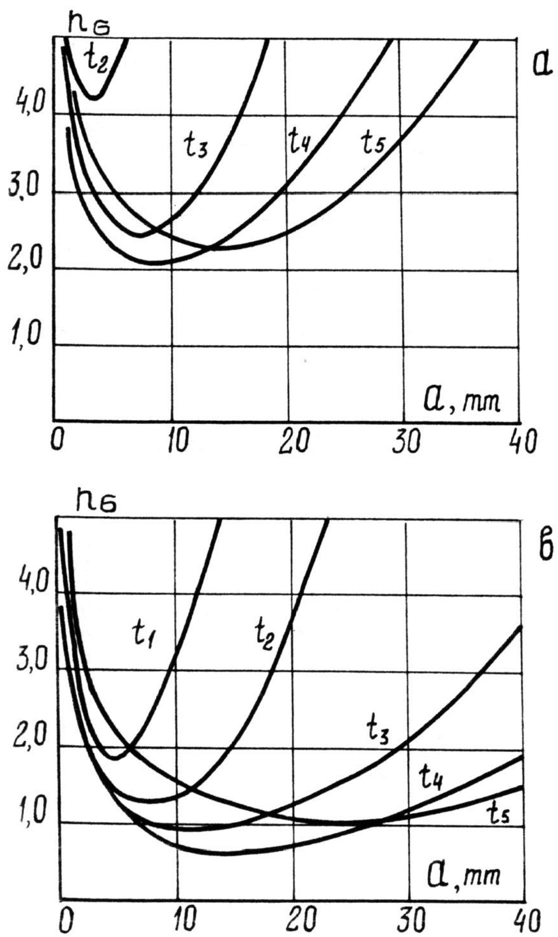

Figure 1 Safety Factor versus Crack Depth for Various Periods of Time from the Cooling Moment (t_1 = 77s, t_2 = 96s, t_3 = 109s, t_4 = 122s, t_5 = 150s) and T_D = 30° (a) and T_D = 70° (b)

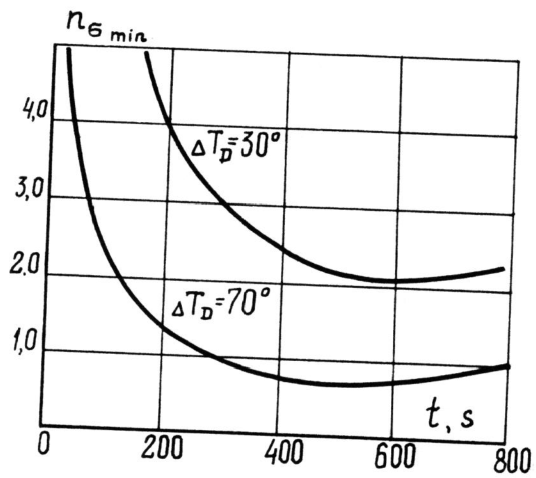

Figure 2 Minimum Safety Factor Values versus Time from the Cooling Moment