VLIV VELIKOSTI NA KOROZNÍ ÚNAVOVOU PEVNOST LITÉ OCELI 13%Cr-4%Ni

SIZE EFFECTS ON THE CORROSION FATIGUE STRENGTH OF 13%Cr-4%Ni CAST STEEL

David Varner [a] and Miroslav Varner [b]

[a] David Varner, Transcad CZ, s.r.o.Blansko, Czechia
[b] Miroslav Varner, Litostroj Engineering a.s.Čapkova 2357/5, 67801 Blansko, Czechia

Abstrakt

V příspěvku se uvádí statistický, geometrický a technologický vliv velikosti rozměrných dílců vyrobených z lité oceli 13%Cr-4%Ni na jejich korozně únavovou pevnost při počtu kmitů zatížení vice než milión. Vlivy velikosti a jejich parametry jsou odvozeny s použitím Weibulovy distribuční funkce a výsledků únavových zkoušek hladkých a vrubovaných tyčí ve vodě. Haighův diagram velkých vrubovaných tyčí byl použit pro ověření vlivu velikosti. Popsané vlivy velikosti se doporučují využívat při hodnocení spolehlivosti vodních turbín.

Abstract

The article deals with the statistical, geometric and technological size effects on the corrosion fatigue strength of large parts made from the 13%Cr-4%Ni cast steel for loading cycle number greater than a million. The size effects and their parameters are derived using the Weibull distribution and the results of corrosion-fatigue tests on smooth and notched specimens. Haigh diagram of large notched specimen was used for verification of the size effects. The reported size effects are recommended in reliability evaluation of water turbine.

Introduction

The hydraulic and mechanical design of water turbines uses computer simulations of both water flow and mechanical stresses. The simulations provide reliable information about the stress distribution of the parts under the actual pressure load of flowing water [1]. The estimations of part corrosion fatigue strength (*CFS*) necessarily require additional data on material properties. These are, however, influenced by the type of steel, technology, volume, shape and surrounding environment. Material properties determined experimentally are used to model of parts fatigue properties [1], [2] and [3].

In order to calculate the *CFS* or lifetime of loaded water turbine part from experimental results acquired using small specimens in laboratory tests, three types of size effect have been generally considered: statistical size effect, geometrical size effect and technological size effect.

The statistical size effect is caused by the occurrence of micro-discontinuities, e.g. micro-cracks, porosity, inclusions [4] and some local weakened passive layers [5] and [6], with a random distribution in areas exposed to corrosion fatigue of macroscopically homogeneous parts of the casting.

The geometrical size effect is dependent by stress relative gradient in the notch root [4]. The effect is caused by the material anisotropy and size of elementary particles and their supporting effects that occur in and under the root of the notch.

The technological size effect is caused by macroscopic surface or volume inhomogeneity in the distribution and properties of microdefects that arise during steel pouring and casting solidification [7] and [8]. The technological effect of the size depends on the casting modulus, the thickness of the casting and the location in the casting [9].

The article presents derivation of the size factors formulas and their parameters based on the results of fatigue tests of Cr13%-4%Ni cast steel specimens in neutral tap water [9], [10] and [11]. Experimental Haigh diagram of a large notched specimen made from 13%Cr-4%Ni cast steel [11] loaded in water is used to verification of the *CFS* calculation. This approach is necessary especially for large water turbine cast where are appreciable size effects on corrosion fatigue crack initiation.

Statistical Size Effect

The statistical size effect is described by the Weibull reliability function derived from the Weakest-Link Model [12]:

$$R = \exp\left[-\frac{A}{A_{ref}} \cdot \left(\frac{S_{aC}}{\delta}\right)^{c}\right], \text{ for } S_{aC} > 0, \qquad (1)$$

where $R \in (0, 1)$ is reliability or survival probability, S_{aC} is *CFS* amplitude, δ and c is scale and shape parameter respective of the Weibull distribution, A_{ref} is surface area reference of smooth specimen and A is a part surface area with stress field $S = S(x, y, z)$ and maximum notch stress S_{max}. The area A is given by the stress integral [12]:

$$A = \int_A g(x,y,z)^c dA, \text{ with } g(x,y,z) = S(x,y,z)/S_{max}. \qquad (2)$$

Statistical size factor SSF of a part with fatigue exposed area A is defined by ratio of the *CFS* limit $S_{aC}(R, A)$ and $S_{aC}(R, A_{ref})$, which are obtained by modified equation (1):

$$SSF(A) = \left(\frac{A_{ref}}{A}\right)^{\frac{1}{c}}. \qquad (3)$$

Note: The *SSF* value does not include the usual R survival probability requirement against a survival probability of $R = 0.5$. Therefore, a special reliability factor needs to be taken into account when calculating the *CFS* for $R \neq 0{,}5$. Reliability factor *RF* is described by formula:

$$RF(R) = \left(\frac{\ln (R}{\ln (0.5)}\right)^{\frac{1}{c}}. \qquad (4)$$

Parameters of the Weibull reliability function at $A = A_{ref}$ are calculated (1) from *CFS* amplitudes $S_{aC}(R = 0{,}5)$ and $S_{aC}(R = 0{,}9)$ which are acquired from results of corrosion fatigue tests [10] and [11]. The calculated Weibull reliability functions of the reference specimen for the load cycle range $N \in \langle 10^6, 10^{11} \rangle$ and of the part with $A = 10 \cdot A_{ref}$ for $N = 10^{11}$ are shown in Figure 1.

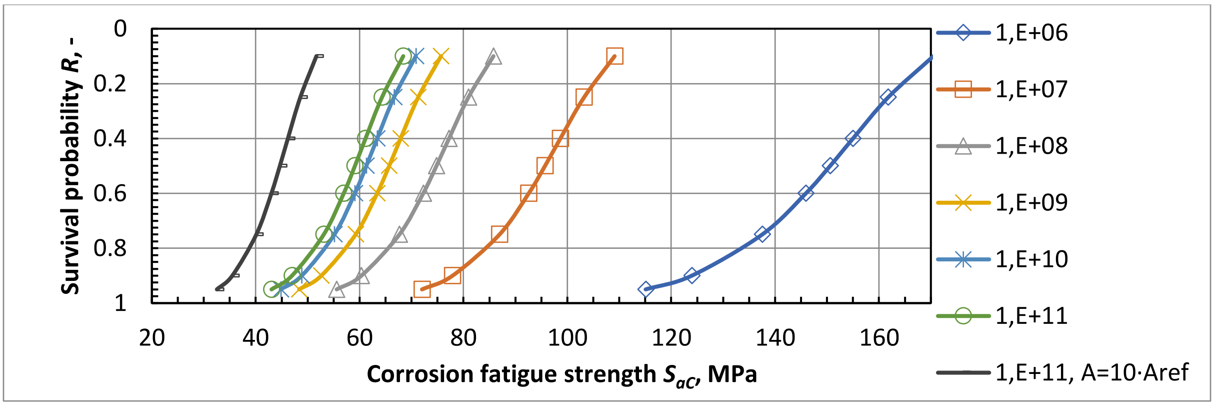

Figure 1 Survival probability of 13%Cr-4%Ni cast steel specimens/part loaded in water

Geometric Size Effect

Relative stress gradient κ describes influence of stress non-homogeneity at the notch root on the *CFS* using the following formula [4]:

$$\frac{\alpha}{\beta} = 1 + (\kappa \cdot C)^{0.5}, \tag{6}$$

where $\alpha = \frac{S_{max}}{S_{nom}}$ is stress concentration factor notch, $\beta = \frac{S_{aC}}{S_{aCnom}}$ is fatigue notch factor, $\kappa = \frac{1}{S1_{max}} \cdot \left(\frac{dS1}{dx}\right)_{x=0}$ is relative gradient of principal stress $S1$ in the notch root, x is the distance from the notch root entered according to the agreement in mm units, C is coefficient depended on material strength, $S1_{max}$ is maximal principal stress in notch, S_{nom} is nominal stress in section under notch, S_{aC} is fatigue strength of smooth specimen and S_{aCnom} is fatigue strength of the notched specimen. Fatigue geometrical size factor of notched specimen (8) includes statistical size effect as well, because the fatigue exposed areas of smooth and notched specimens have different sizes. The calculation of the geometric size factor *GSF* without the statistical size effect is expressed by the relation:

$$GSF = \frac{1}{SSF} \cdot \frac{\alpha}{\beta}. \tag{7}$$

The calculations of the *GSF* are based on the results of corrosion fatigue tests of smooth and notched specimens made from large 13%Cr-4%Ni steel casting [9] and the results of the finite element analysis both of stress concentration factor and of relative stress gradient of notched specimens. Table 2 summarizes input experimental data, stress concentration factor α and relative stress gradient κ and calculation results of α/β, C (8), *SSF* (3) and *GSF* (7). The values of both calculated α/β for $C = 0.130$ (6) and *GSF* (7) in dependency on the relative stress gradient are shown in Figure 2.

Table 1 Input data and calculation results of *GSF*

Experimental data		Computation FEA		Calculation				
S_{aC}, MPa	S_{aCnom}, MPa	α, -	κ, -	β, -	α/β, -	C, mm	*SSF*, -	*GSF*, -
110	104	1.10	0.037	1.048	1.050	0.130	1.047	1.002
110	72	1.91	0.446	1.521	1.256	0.130	1.202	1.045

It is clear that the geometric size effect on the *CFS* of notched parts is marginal compared to the statistical size effect.

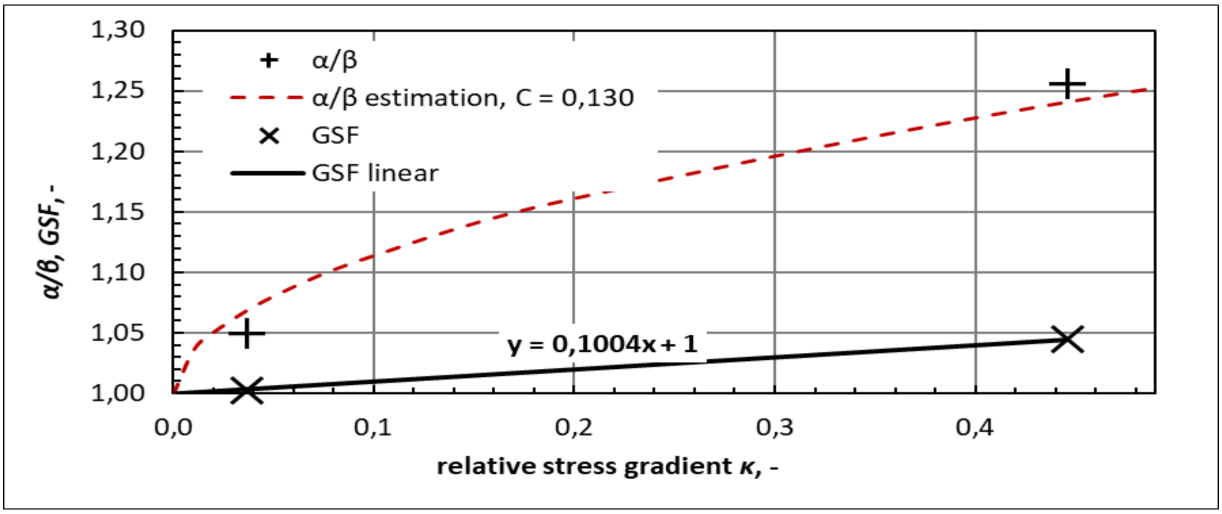

Figure 2 Geometrical size effect of Cr13%-4%Ni cast steel specimens loaded in water

Technological Size Effect

The technological size effect is caused by macroscopic inhomogeneity in chemical composition and by both distribution and feature of steel and passive layer microdefects. The specimen of a core of thick wall (500 mm) casting from 13%Cr-4%Ni steel shows a 20% lower *CFS* than specimen of casting rim, which was solidified and heat-treated under optimal conditions [7] and [8]. The effect of casting size on its surface and in its core on the *CFS* of large notched specimens at $N = 10^7$ is published [9]. Technological size factor of large notched specimens:

$$tsf(t) = \frac{S_{AC}(t)}{S_{AC}(500\,rim)} \tag{8}$$

is equal 1 for rim of cast with thickness $t = 500$ mm (cast modulus 13), $tsf = 1.13$ for rim of cast and core of cast with $t = 150$ mm (cast modulus 5.5) and $tsf = 0.87$ for cast core of casting with $t = 500$ mm. Technological size factor of smooth specimen with reference size [9] is defined by ratio:

$$TSF(t) = \frac{S_{aC}(t)}{S_{aC}(500\,rim)}. \tag{9}$$

CFS of large notched specimens manufactured from cast rim with thickness *t* and reference cast rim (*t*=500 mm) are given by the Marin´s formulas [13]:

$$S_{ACmax}(t) = k_s \cdot SSF(t) \cdot TSF(t) \cdot GSF \cdot S_{aC}(\,500\,rim) \tag{10}$$

and

$$S_{ACmax}(500\,rim) = k_s \cdot SSF(500\,rim) \cdot 1 \cdot GSF \cdot S_{aC}(\,500\,rim). \tag{11}$$

By substituting equations (13) and (14) into equation (11) and modifying it, we obtain the following relation:

$$TSF(t) = tsf(t) \cdot \frac{SSF(500\,rim)}{SSF(t)}. \tag{12}$$

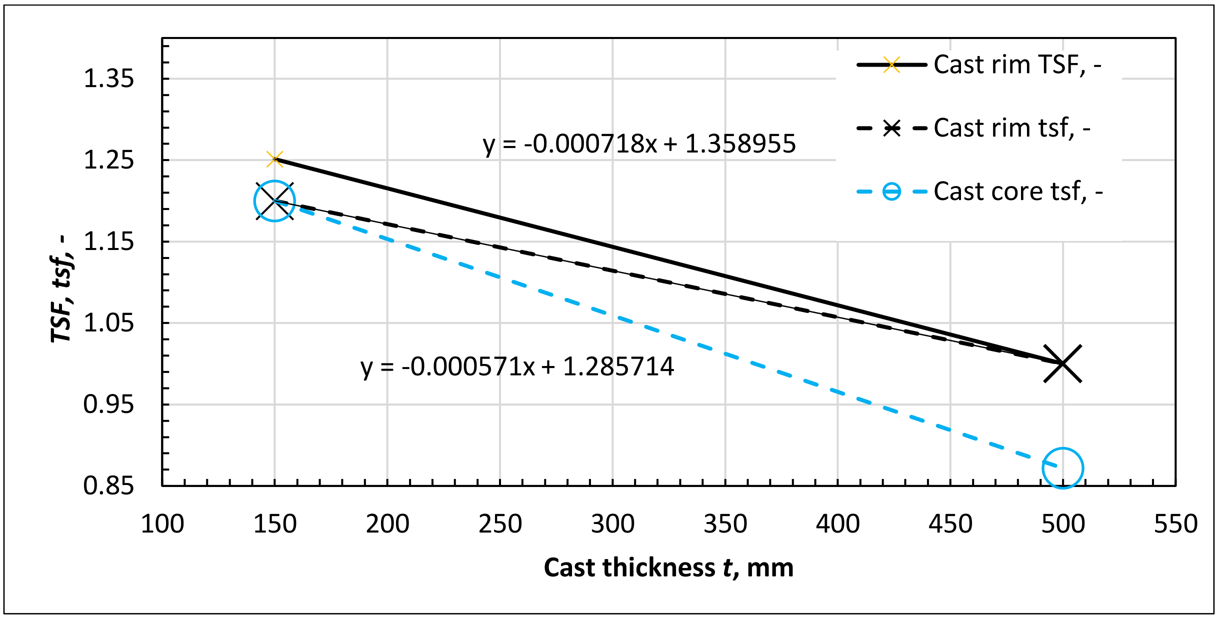

Figure 3 Technological size factor *tsf* and *TSF* versus thickness *t* and location in cast [17]

Technological size factors *tsf* and *TSF* of cast part versus cast thickness *t* and location in cast part are drawn in Figure 3. The technological effect of size, describing the influence of the macroscopic inhomogeneity of the distribution and properties of microdefects and the passive layer of the cast rim on *CFS*, can be considered as a linear in the first approximation:

$$TSF = -0{,}000718 \cdot t - 1{,}359. \tag{13}$$

Verification

Verification of size effects for loading in water is based on comparison of the calculated Haigh diagram from the Sonsino´s corrosion fatigue data of smooth specimen Φ 16 mm in push-pull loading in water [10] and experimental Mahnig´s [11] and Gessmann´s [9] *CFS* data (large notched 13%Cr-4%Ni cast steel specimen of dimensions 300x82x70 mm and 500x100x40 mm, respectively).

Calculated and experimental results of the CFS S_{Acmax} and mean value S_m are the maximum stresses in the notch. Corrosion fatigue strength $S_{ACmax}(N, S_m, R=0.5)$ of a large notched specimen from cast according to Marin [13] is given by formula:

$$S_{ACmax}(N, S_m, t, R = 0.5) = k_s \cdot TSF(t) \cdot SSF(c, A_{ref}, A) \cdot GSF(\kappa) \cdot S_{aC}\left(N, S_m, A_{ref,}\, R = 0.5\right)$$

where $S_{aC}(N, S_m, R = 0.5)$ is Haigh diagram of smooth specimen, k_s is ratio of notched and smooth reference specimen surface quality coefficients. Experimental and calculated *CFS* of a large notched specimen is presented in the Figure 4.

The calculated prediction of the CFS of the large notched specimen complies with experiment results. The deviation of the CFS calculated prediction of the notched body does not have a cumulative character as the number of load cycles increases. Therefore, the described calculation approach of size factor can be recommended for use in engineering practice.

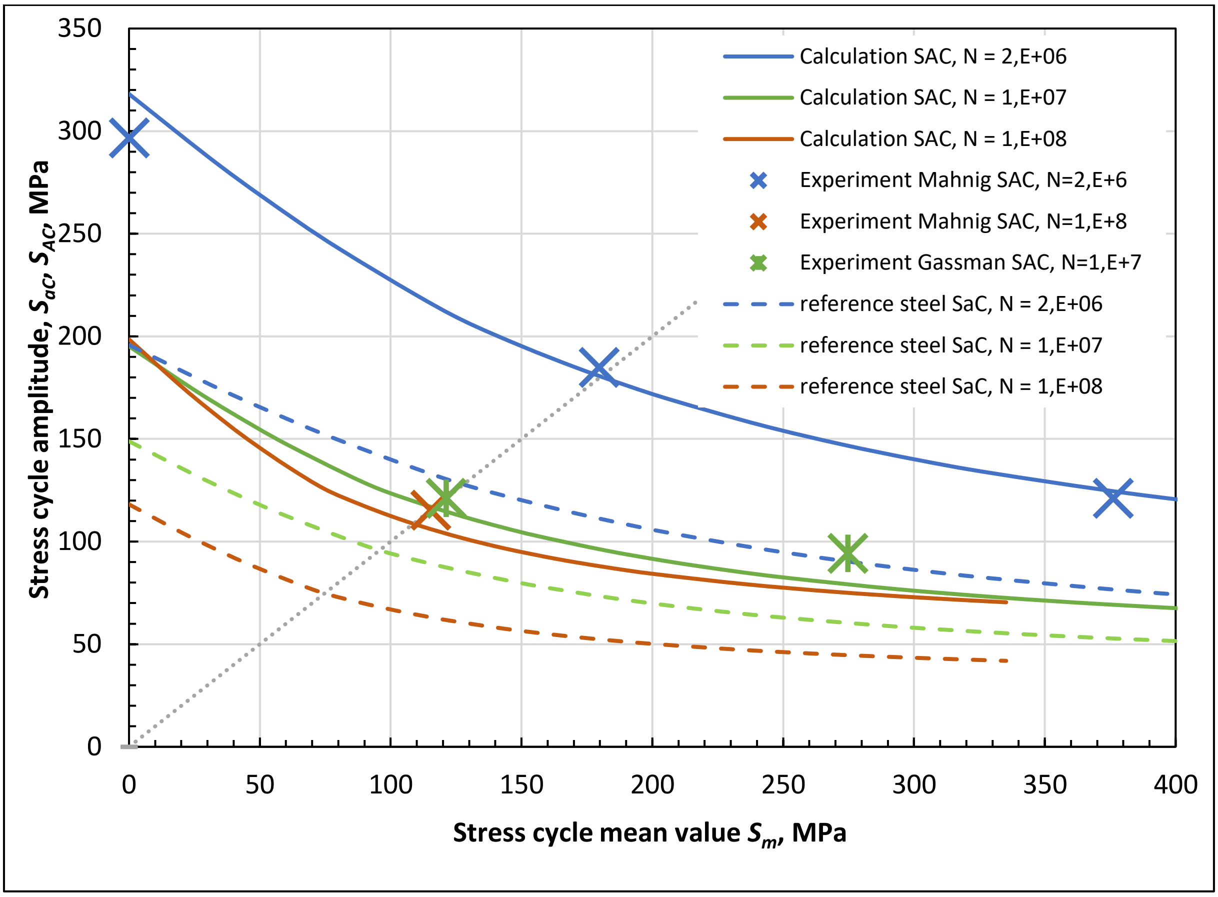

Figure 4 Calculated Haigh diagram of a large bended specimen in water

Conclusion

The statistical, geometrical and technological effect of the size and the decisive importance of the application of the Weibull distribution in the corrosion fatigue of steel castings 13%Cr-4%Ni are analyzed. Formulae describing size effects are derived. The scale parameters value of the Weibull distribution depending loading on both cycle number and corrosion fatigue strength amplitude are presented. The technological size factor is quantified for smooth reference specimens for variable cast thickness. The values of the parameters of linear relation describing the geometrical size effect on corrosion fatigue strength are also given.

Experimental Haigh diagram and calculated Haigh diagram of a large notched specimen loaded in water was used for verification of the calculation approach. Coincidence of calculated and experimental corrosion fatigue strength is significant. The fundamental significance of the technological and statistical size effects on the corrosion fatigue strength of large notched specimens was found, while the geometrical size effect is marginal.

Corrosion fatigue strength S_{ACmax} for the given number of load cycles N, mean stress *Sm*, thickness t and reliability R of a notched part made from 13%Cr-4%Ni cast steel with corrosion fatigue strength described by Haigh diagram of the smooth specimens $S_{aC}(N, S_m, R = 0.5)$ can be estimated by the symbolic equation:

$$S_{ACmax}(N, S_m, R) = k_s \cdot RF(c, R) \cdot TSF(t) \cdot SSF\left(c, A_{ref}, A\right) \cdot GSF(\kappa) \cdot S_{aC}\left(N, S_m, A_{ref,}\ R = 0.5\right).$$

The reported size effects on the corrosion fatigue strength can be recommended for reliability assessment of water turbine parts.

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