Journal of Polish CIMAC
Gdansk University of Technology
The Faculty of Ocean Engineering and Ship Technology

INVESTIGATING THE SIZE EFFECT FOR THE SMALL-DIMENSION SPECIMENS MADE FROM THE EN AW-6063 ALUMINUM ALLOY

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Abstract

The paper concerns the size effect on fatigue life and fatigue strength. As for the mini specimens, smaller than the normative specimens, they show an increase in fatigue life with a decrease in the object cross-section area. Theoretically the calculational models assume a lack of sensitivity of the aluminum alloys to changes in the cross-section size, which is contrary to the experimental tests. The paper has been an attempt at determining the size effect for EN AW-6063 aluminum alloy mini specimens. Monotonic and fatigue tests were made. There were observed correlations of the results for the coefficient of material sensitivity to change in the cross-section. The results have made it possible to define the relationship of the ultimate tensile strength and fatigue strength for the specimens of various size.

Keywords: *size effect, σ_a-N_f curve, high- cycle fatigue, mini specimen*

1. Introduction

Fatigue characteristics defined with the use of specimens tested in laboratory conditions will be different than the characteristics for the real design object made from the same material, which is accounted for e.g. the size effect which describes the sensitivity of the material to the change in the area of the cross-section. Disregarding this effect often results in the occurrence of fatigue cracks much below the fatigue limit determined in laboratory conditions. Even though the size effect was experimentally tested for large and mini specimen sizes, frequently the implementation of that knowledge for specific conditions triggers many problems.

The paper concerns the size effect on fatigue strength for the specimens smaller than the normative ones. The specimens of the working cross-section from a few to a dozen or so square millimeters show various fatigue life values demonstrating an increase in the fatigue life for smaller cross-sections. The extent of the change in fatigue life is conditioned by the type of the material. The materials of heterogeneous structure or the so called ‘disordered’ ones show a greater sensitivity to the change in the measurements [1]. This information mostly refers to the steels for which the experimental tests results have been given in paper [9]. It is assumed that the size effect is characterized by coefficient [4]:

$$K_d = \frac{Z_d}{Z} \tag{1}$$

where:
- Z_d – fatigue strength of specimen of any cross-section,
- Z – fatigue strength of specimen of the same material, cross-section area 20 ÷ 80 mm^2.

Theoretical calculational models concerning the sensitivity of the material to the changes in the size of the cross-section define the value of coefficient K_d for aluminum alloy at level 1 [6]. The results of experimental tests are, in many cases, different than those assumed above.

As an example, Fig. 1 presents the relationship of the fatigue limit for 10^7 cycles for the specimens cross-section (3.2 mm ÷ 48 mm). The experimental results reported concerned the tests made for 75S-T6 aluminum alloy. The specimens were tested in the rotary bending. The specimens were round in a shape of the hourglass [3]. The results reported identified the size effect where the higher the cross-section, the considerably lower the fatigue strength. According to those authors [4], as a result of a greater specimen volume there is a greater probability of the occurrence of inclusion initiated cracks.

There was observed an ambiguity of the calculational models and the testing results. For that reason there was experimentally verified the size effect for the specimens smaller (mini specimen) than the normative ones. It is justifiable to perform tests for mini specimens due to numerous advantages of tests involving mini specimens. One of them is the case when making a normative specimen is restricted by the measurements of the objects investigated. One of the solutions is the application of mini specimens [10]. The scope of interest of the specimens dimensions tested is given symbolically in Fig. 1.

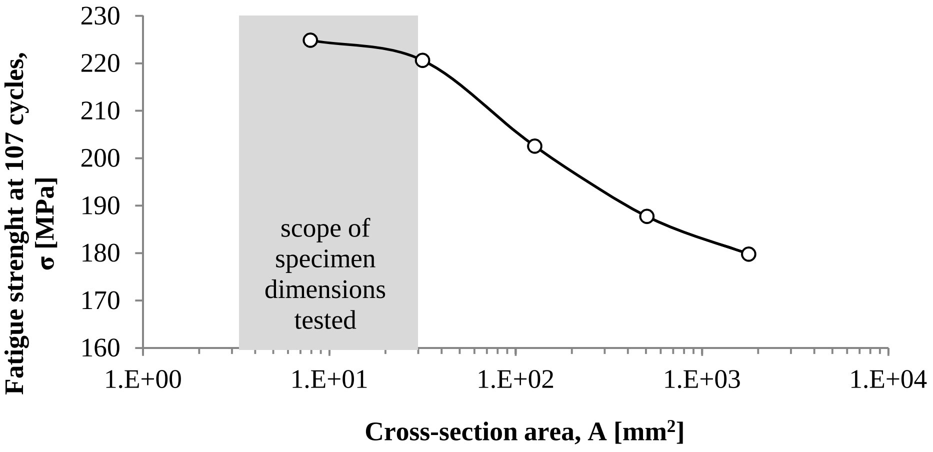

Fig. 1. Dependence of the fatigue limit for 10^7 cycles on the section area of the specimen made from the 75S-T6 aluminum alloy [3]

2. Methodology

The research methodology involves determining:
- the specimens material,
- material strength properties,
- mini and normative specimen geometry for fatigue testing,
- the scope of the stresses applied for high-cycle strength,
- the other fatigue testing conditions (frequency, cycle asymmetry coefficient, testing machine).

To determine the strength properties of the EN AW-6063 aluminum alloy investigated there was made a static tensile test according to [8]. Assuming that the strength properties (yield strength R_e, ultimate tensile strength R_m) of aluminum alloys depend on the section area, the monotonic test was made for normative specimens (the working cross-section of 28 mm^2) (Fig.

2a) and smaller specimens (the working cross-section of 3.5 mm^2) (Fig 2b). The ratio of the cross-section of the normative specimen to the smaller specimen is 8. Compliant with numerous published research results, one can assume that the smaller specimen can be qualified as representing a group of small-cross-section specimens. The results are given in Table 1 and the strain-stress curve in Fig. 3.

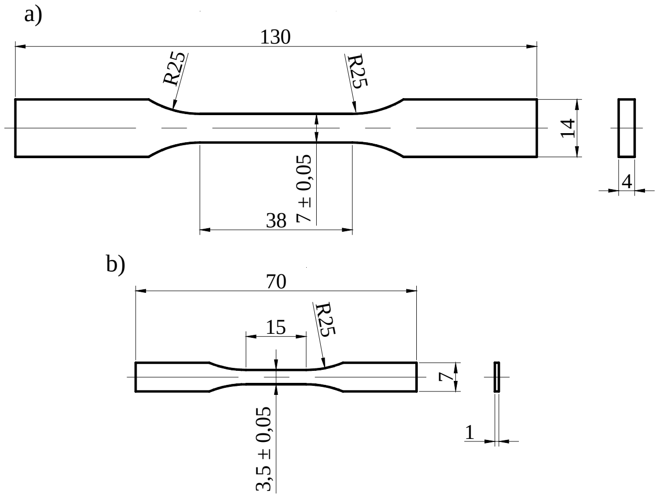

Fig. 2. Specimen geometry for monotonic tests: a) normative [8]; b) smaller

Tab. 1. Mechanical properties of the EN AW-6063 aluminum alloy

Nr	**Normative specimen**				**Smaller specimen**			
	***R_m*, MPa**	***R_e*, MPa**	***A*, %**	***Z*, %**	***R_m*, MPa**	***R_e*, MPa**	***A*, %**	***Z*, %**
1	200	167	16,5	60,4	232	210	12,0	53,9
2	199	165	17,0	62,3	233	209	11,2	54,0
3	207	178	15,6	59,1	230	208	10,4	48,4
4	202	170	17,2	62,7	230	210	11,2	52,0
5	199	167	16,8	61,6	227	207	11,2	52,0
Average	**200**	**167**	16,6	61,2	**230**	**208**	10,8	53,0

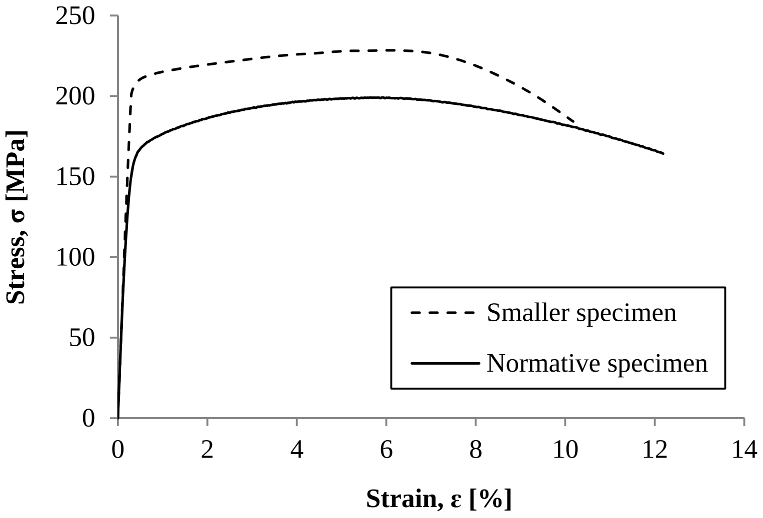

Fig. 3. Strain-stress curve for normative and smaller specimens

The results for monotonic tests demonstrated other values of strength properties. For normative specimens, the ultimate tensile strength was 15 % higher and the yield strength – 25 % higher than for the smaller specimens. Parameters A (a 35 % decrease) and Z (a 13.4 % decrease) behave opposite.

High-cycle fatigue strength tests were made based on the normative specimen and the mini specimen (Fig. 4). There was eliminated the effect of the specimen shape on the results of experimental tests by applying the same theoretical stress concentration factor (α_k) equal 1.05.

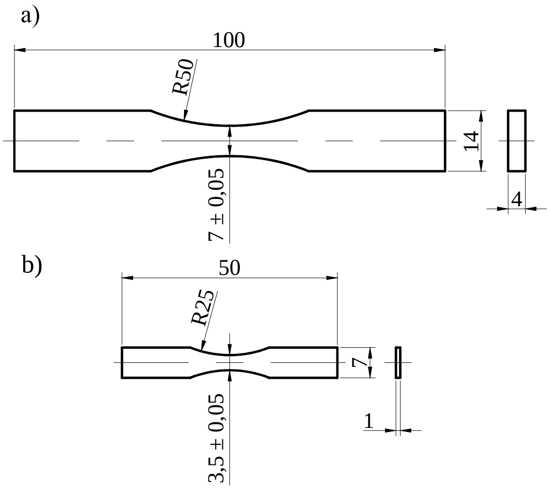

Fig. 4. Specimen geometry for fatigue tests: a) normative [7]; b) mini

The scope of the loads applied in fatigue testing for the aluminum alloy was much above the yield strength (R_e). The material tested showed no stability of the cyclic properties. Tests were made into the strength properties of the cyclically pre-strained specimens. There was noted a 15 % increase in yield strength. The changes observed in the material properties are accounted for by cyclic hardening of the cyclically pre-strained specimens. The results have made it possible to reject the yield strength as the key criterion of high-cycle fatigue strength. A detailed report on testing and the results is covered in paper [10].

Fatigue testing was performed for high-cycle strength. To avoid specimens buckling, there was applied the cycle of the a change in load of cycle asymmetry coefficient $R = 0.1$. The tests were made at the frequency of the load change of 5 Hz. Fatigue and monotonic tests were performed using the Instron 8874 servo-hydraulic material testing machine (Fig. 5). The monotonic tests applied the extensometer of the measurement length of 25 mm.

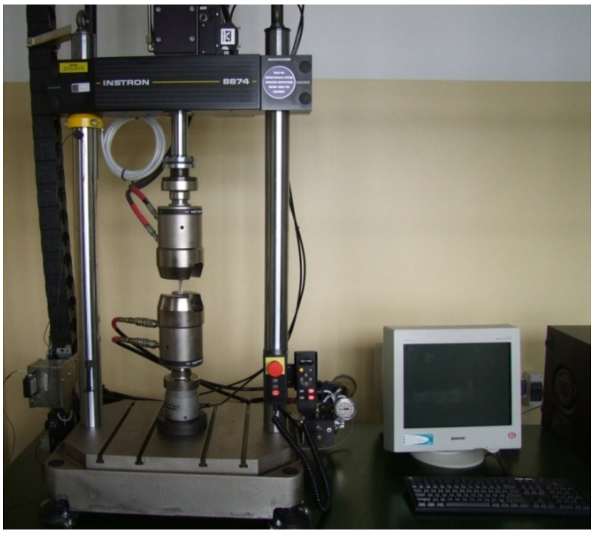

Fig. 5. Servo-hydraulic material-testing machines, Instron 8874

3. Results

3.1. Own testing results

Own fatigue tests were made based on the research methodology described. The macro crack has been assumed as the criterion of the end of fatigue testing. For the results received (the σ_a-N_f curve, Fig. 6, Table 2) with the use of the mini specimen, there was plotted a line of regression (slope m = 12.4) of the coefficient of determination at the level of 0.93.

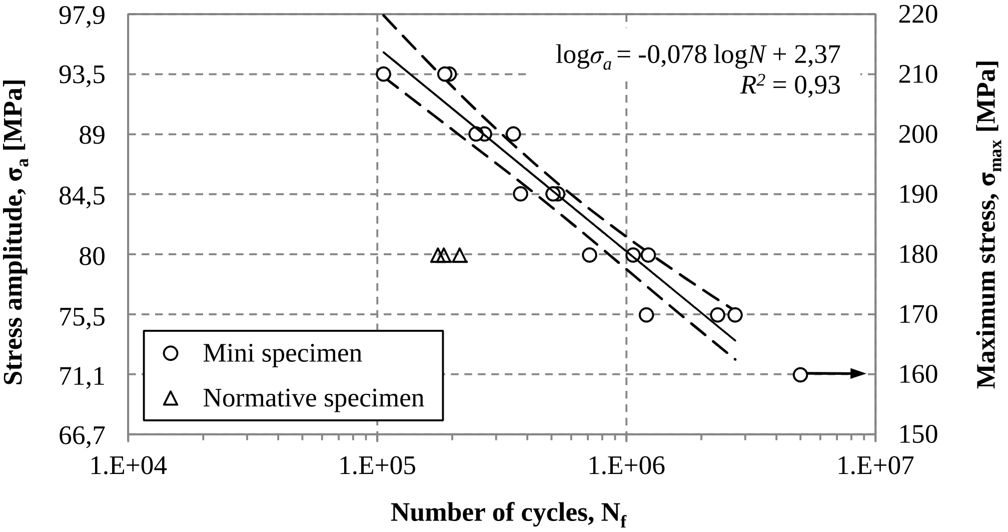

Fig. 6. σ_a-N_f curve for EN AW-6063 aluminum alloy

Tab. 2. Fatigue test results

Specimen	**Maximum stress, σ_{max} [MPa]**	**Number of cycles, N_f**	
		For specimen	**Average**
Mini	210	105 970	162 521
		186 811	
		194 782	
	200	249 372	290 347
		269 602	
		352 067	
	190	376 419	471 783
		508 524	
		530 407	
	180	712 051	1 001 094
		1 065 530	
		1 225 700	
	170	1 205 043	2 088 888
		2 327 384	
		2 734 238	
	160	5 000 000	5 000 000
Normative	190	214 033	191 360
		184 952	
		175 094	

Fig. 7 presents the location of the macro crack against the geometrical center of the specimen (the ratio of the distance of fatigue fracture from the specimen center (a) to the specimen width (b)). It demonstrates a random distribution. There was observed no effect of the geometry shape and other factors on the test results. The results which were considered credible were only those when the specimen got destroyed in the distance not greater than 1.5 mm from the center. The specimens destroyed in the assumed crack range are given in Fig. 8.

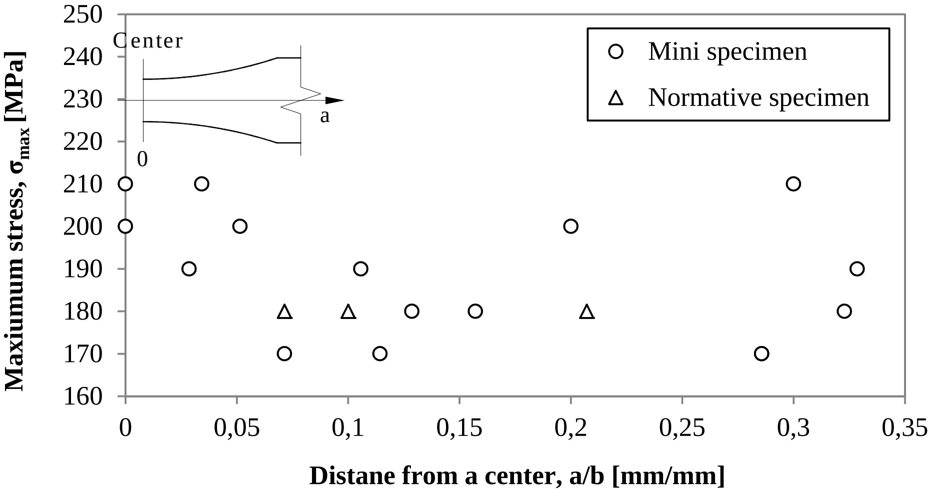

Fig. 7. Location of specimens crack for maximum stresses

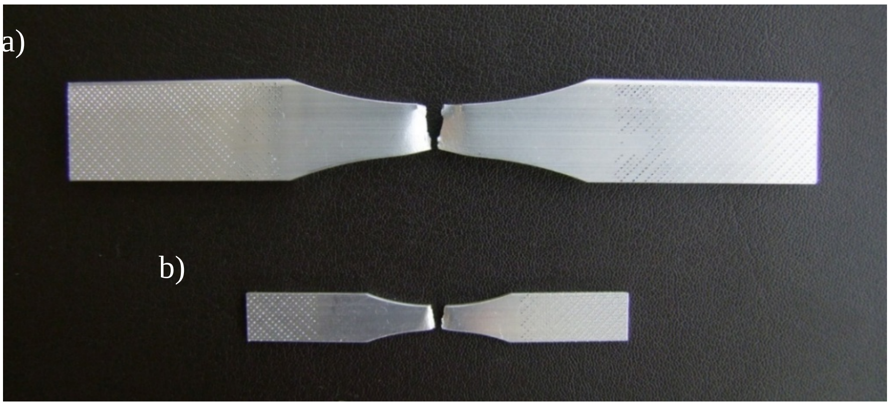

Fig. 8. Photograph of the crack location: a) normative specimen; b) mini specimen

3.2. Testing results reported in literature

The results of experimental tests for the EN AW-6063 aluminum alloy at state T7 for the high-cycle fatigue range have been described in detail in paper [5]. The tests involved determining the effect of material properties (the chemical composition, microstructure, thermal treatment) on material fatigue properties. The material used showed tensile strength at the level of 213 MPa and yield strength 186 MPa. Fig. 10 presents the σ_a-N_f curve for the results reported with the use of the normative specimen (Fig. 9) compliant with the ASTM E466-96 standard.

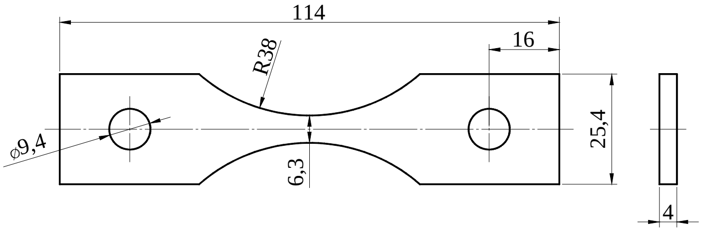

Fig. 9. Geometry of fatigue test specimen used in work [5]

The specimens were tested at the frequency in the range from 30 to 70 Hz. There was applied the sinusoidal cycle of cycle asymmetry coefficient $R = 0.1$. The tests parameters and results reported are comparable with those reported in own tests (3 samples at the level of stress amplitude of 80 MPa), and as such they were used for the purpose of the analysis of the results.

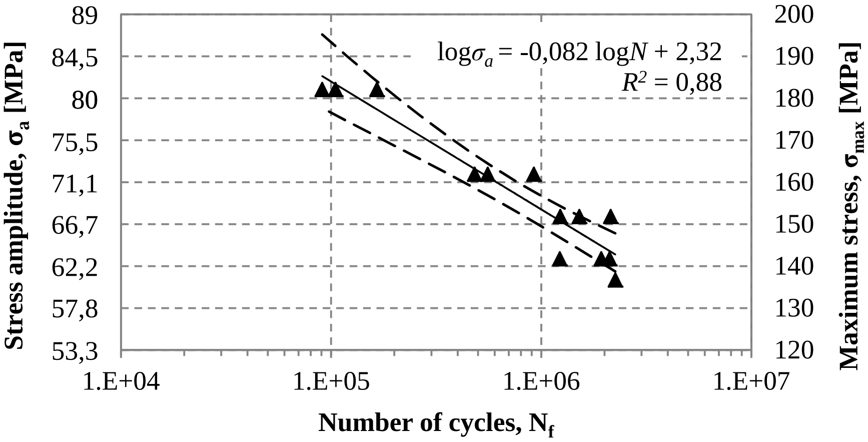

Fig. 10. σ_a-N_f curve for EN AW-6063 aluminum alloy [5]

4. Statistical analysis

The statistical analysis of the tests results involved the test of parallelism for the slope (a) of the regression function ($y = ax + b$) [2]. The aim was to verify the null hypothesis (H_0) on the significance of the coefficients of linear regression recorded for the tests. The alternative hypothesis (H_1) assumed various values of the slope of the line. The hypothesis were formulated as follows: H_0: $a_1 = a_2$, H_1: $a_1 \neq a_2$.

There were received regression lines of the fatigue tests results (Fig. 11) for:

- normative specimen (according to source [5]): $\log\sigma_a = -0.082 \log N + 2.32$
- mini specimen: $\log\sigma_a = -0.078 \log N + 2.37$.

The hypothesis was verified using the test of significance for two regression coefficients. The hypothesis was verified for the results received with the use of the mini specimen (own experiments) and the normative specimen (literature source [5]).

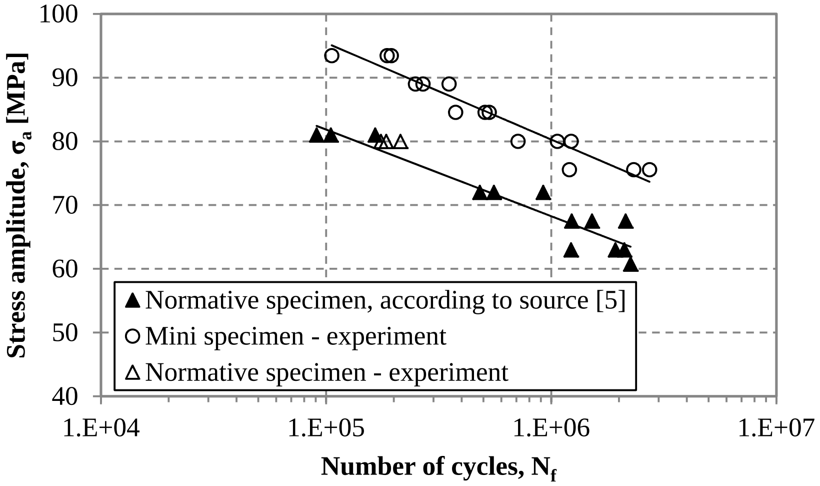

Fig. 11. Breakdown of the experimental tests results for the EN AW-6063 aluminum alloy

The value of test statistics t was determined for the degrees of freedom $n_1 = 13$ (the normative specimen), $n_2 = 15$ (the mini specimen). Critical value t_{tab} was read from t Student distribution for $n_1 + n_2 - 4$ degrees of freedom of the two-tailed critical area. The test of parallelism was made at the significance level of $\alpha = 0.05$. Inequality $|t| < t_{tab}$ was received. There are no grounds for rejecting null hypothesis H_0 of the equality of the slopes of regression lines for σ_a-N_f curves of the normative and mini specimens. The variable parameter is the absolute term (b) of the equation of a straight line. For that reason the size effect can be described with the coefficient of the cross-section size K_d which, for the fatigue tests results reported was equal to 1.17.

5. Conclusions

There was investigated the size effect for the EN AW-6063 aluminum alloy within the scope of high-cycle fatigue. The experimental tests (monotonic, fatigue) results identified the material susceptibility to changes in the cross-section size for the specimens smaller (mini specimen) than the normative ones. The tensile strength/fatigue strength of mini specimens was higher than that of the normative specimens. Thanks to the statistical analysis made it was possible to verify the hypothesis of the parallelism of σ_a-N_f curves of the specimens geometry tested. The coefficient of cross-section size K_d for the values reported for monotonic specimens was determined (for tensile strength – 1.17) and fatigue tests (for fatigue strength – 1.15). The present tests suggest that the convergence of results makes it possible to refer coefficient K_d from monotonic tests directly to fatigue tests, which needs further verifying.

Defining the coefficient of the size effect for a material is an essential stage for referring the σ_a-N_f fatigue curve to the real object. Disregarding the effect of the cross-section size can be can trigger the occurrence of the fatigue fracture much below the characteristics determined for the normative specimens and the mini specimens.

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