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APPLICATION OF MINI SPECIMENS TO HIGH-CYCLE FATIGUE TESTS

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Abstract

Determining complete material fatigue characteristics (S-N curve) is time-consuming and very expensive. Searching for faster procedures of determining the S-N curve, one can use approximate methods which are burdened with qualitative and quantitative error. Such characteristics differ from the real experimental studies results. Yet another method involves the use of mini specimens; the specimens the dimensions of which are lower than the normative sample. It allows for performing tests using much cheaper test stands. In the specimens researched there is a size effect which is broadly discussed in the available literature. The present work offers a review of the current theoretical knowledge on the size effect. There was analysed the geometry of mini specimens applied in experimental studies. Selected works with the use of mini specimens have been reviewed. Areas have been defined in which the mini specimen application is justifiable.

Keywords: *size effect, mini specimen, S-N curve, fatigue*

1. Fatigue tests in the high number of cycles range

An indispensible part of calculations of design elements exposed to fatigue loads is the knowledge of basic material characteristics, namely the Wöhler characteristics, also referred to in literature as the S-N curve (Fig. 1). In the range of high number of cycles it shows two characteristic areas; limited fatigue life (the area under the section defined with slope m, but above Z_G) and unlimited fatigue life (the area below Z_G).

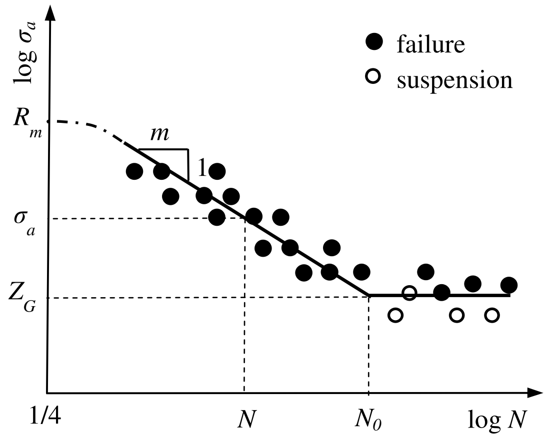


Fig. 1. S-N curve plotted on log σ_a – log N coordinates

The diagram presented (Fig. 1) shows approximate numbers of specimens necessary to determine the S-N curve. The tests are performed in the area of high-cycle fatigue life in the range 5 x 10^3 cycles to 2 x 10^6 to 10 x 10^6 cycles (N_0). The tests are therefore very time-consuming. To perform such tests, typical servo-hydraulic material-testing machines are used (Fig. 2). The cost of these machines, plus additional indispensible equipment (e.g. extensometer) is, in the case of normative specimens, very high (a few hundred thousand Euro), which makes us encounter material testing machines only in a few laboratories, which, in turn, implies the situation that the real fatigue tests to determine the real Wöhler characteristics, are performed quite rarely. Even if executed, they are considered very expensive due to their time-consuming nature and the high cost of equipment.

Fig. 2. INSTRON servo-hydraulic material-testing machines, laboratory of University of Technology and Life Science

With that in mind, literature offers proposals of approximate definition of the quantities determining the S-N curve. Importantly, the methods are always burdened with a considerable quantitative and qualitative error. They are not, therefore, and cannot be in the future a replacement for real experimental tests.

One of the ways to find a compromise between the identified, due to the accuracy, justification of performing experimental tests and the tests costs is the use of specimens small in size (mini specimens). In the mini specimens tests one can use the test stands of a very simplified structure, due to the range of forces applied. A direct use of the mini-specimen test results calls for determining the size effect on the results and defining, due to normative definition missing, what the mini specimen is.

2. Literature approach to the size effect

Most works [6, 7, 9] assume that fatigue strength decreases with an increase in the dimensions of the element. A graphic representation of that effect is given in Fig. 3. The size effect is explained based on the probabilistic models referring back to the probability of destroying the weakest link in the material structure in the cross-section analysed. With the material volume getting bigger and bigger, there increases the probability of the occurrence of material defects which are caused by the centre of fatigue cracking. This physical model of the size effect, however, is not reflected in the recommended relationships to be applied. It is assumed that the size effect is characterised by the co-efficient [6]:

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

where:
- Z_d – fatigue strength of specimen of any diameter,
- Z – fatigue strength of specimen of the same material, diameter 7 ÷ 10 mm.

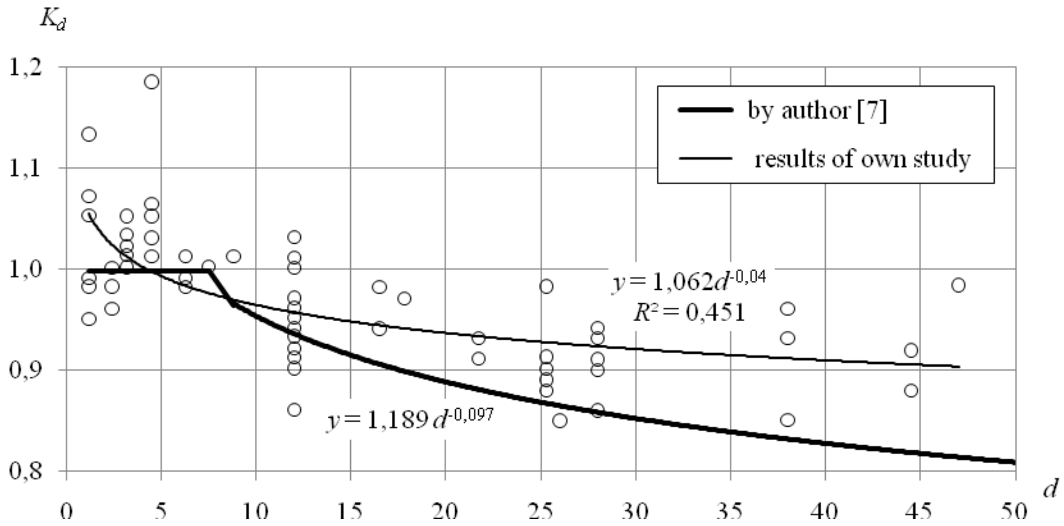


Fig. 3. Quantitative description of the size effect (K_d) [7]

Work [9] makes values K_d depend on the material the element has been made of:

a) for grey cast iron:

$$K_d = \begin{cases} 1{,}207 & \text{for } d \le 7{,}5, \\ 1{,}207\left(\dfrac{d}{7{,}5}\right)^{-0{,}1922} & \text{for } d > 7{,}5, \end{cases} \tag{2}$$

where:
- d – specimen diameter [mm].

b) for stainless steel within the dimensions given in material standards:

$$K_d = 1, \tag{3}$$

c) other types of steel and cast iron materials:

$$K_d = \begin{cases} 1 & \text{for } d \leq d_{min}, \\ \dfrac{1 - 0{,}7686\ a_d \lg\left(\frac{d}{7{,}5}\right)}{1 - 0{,}7686\ a_d \lg\left(\frac{d_{min}}{7{,}5}\right)} & \text{for } d_{min} < d \leq d_{max}, \\ \dfrac{1 - 0{,}7686\ a_d \lg\left(\frac{d_{max}}{7{,}5}\right)}{1 - 0{,}7686\ a_d \lg\left(\frac{d_{min}}{7{,}5}\right)} & \text{for } d \geq d_{max}, \end{cases} \tag{4}$$

where:
- d_{min} – diameter complied with table in work [9],
- d_{max} – maximum diameter adopted in experiment,
- a_d – co-efficient complied with table in work [9].

d) for wrought aluminium alloys (although R_m, depend on the diameter or thickness of the component):

$$K_d = 1, \tag{5}$$

e) for cast aluminium alloys:

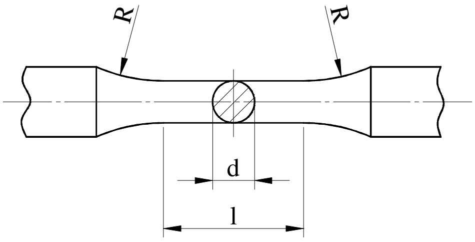
$$K_d = \begin{cases} 1 & \text{for } d < 12, \\ 1{,}1\left(\dfrac{d}{7{,}5}\right)^{-0{,}2} & \text{for } 12 < d \leq 150, \\ 0{,}6 & \text{for } d \geq 150, \end{cases} \tag{6}$$

The co-efficient of the size effect is mostly introduced in the elements exposed to bending and torsion. At those states of load the susceptibility to the size effect is clearly connected with the gradient of stress (strain). In the specimens with axial load the gradient of macroscopic stresses does not exist and so in some works, e.g. [6] it is assumed that there is no need to apply the co-efficient. Direct fatigue tests, however, demonstrated a little impact of the size effect for components with axial load and its application is recommended, which is reported by e.g. work [7].

The analysis of the range of diameter from 8 to 40 mm is covered by work [2] which presents the size effect based on the fractal theory referring back to the material structure. The fractal theory concerns the description of plants of irregular structure magnified to any extent. The ultimate tensile strength and fatigue life were decreasing with an increase in the specimen size. The decrease is relatively bigger for materials showing structure heterogeneity. Increasing the volume of the design element there increases the probability of damaging the element due to greater probability of finding critical micro-fractures causing the development of the fracture.

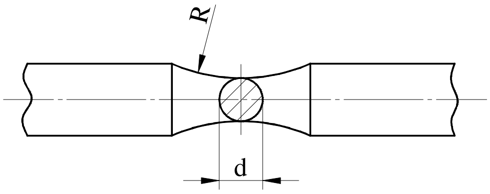
3. Mini specimen geometry

The results of experimental studies reported in other works [3, 4, 5] were recorded for reference specimens (normative) the shape of which complied with standard PN-74/H-04327 [10] (Figs 4, 5).



d [mm]	l [mm]	R_{min} [mm]
6	24	24
7,5	30	32
10	40	45
12	48	48

Fig. 4. Geometry round specimens of a fixed cross-section [10]



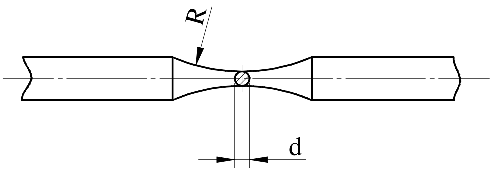
d [mm]	R_{min} [mm]
6	24
7,5	32
10	45
12	48

Fig. 5. Geometry round specimens of variable cross-section [10]

Works [3, 4, 5] were drawing directly on the specimens made according to norm ASTM E-466 [1] for which measurements were defined for round specimens of a fixed cross-section (d = 5.08 mm ÷ 25.4 mm, R_{min} = 8 x l, l = 2 ÷ 3 x d) and round specimens of variable cross-section (d = 5.08 mm ÷ 25.4 mm, R_{min} = 8 x d).

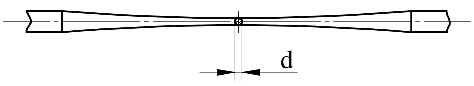
Mini specimens in literature are various in shape. There dominates the shape similar to the normative specimen (Fig. 6a), namely a round specimen of varied cross-section in the shape of the hour-glass. This type of geometry shows a good buckling strength, which is an essential aspect in the miniaturization of specimens with axial load, however, it is also useful to tests with a variable bending and turning moment.

a)



d [mm]	R_{min} [mm]	By work
1	36	[4]
2	80	
1,25	10	[5]
3	31	[3]

b)



d [mm]	By work
0,1, 0,2, 0,6	[8]

Fig. 6. Mini specimen geometry round specimens of variable cross-section, complied with work: a) [3, 4, 5], b)[8]

Besides, one can encounter specimens the shape of which is presented in Fig. 7 (the shape conditioned by the initial material for tests) and the samples presented in Fig. 6b (the specimens shape conditioned by the load method, in that case the tensile specimen).

4. Experimental studies referring to the use of mini specimens in tests

Work [5] presents the impact of the size effect on the fatigue life of the irradiated specimens and weldments (TIG) made from Japanese steel of a reduced ferritic-martensitic activity JLF-1

(Fe-9Cr-2W-V-Ta). Steel JLF-1 is used in the structure of shields of nuclear reactors using the fusion reactors D-T. There were applied two kinds of the specimen sizes; the shape complied with the norm ASTM E-606 and the sample diameters equalled 6 mm (normative specimen) and 1.25 mm (mini specimen) (Fig. 7). The samples were exposed to fatigue tests monitoring strain. In both cases (base material and weld material), the mini specimen showed a greater fatigue life that the normative specimen; the original results are provided in Fig. 8 following work [5].

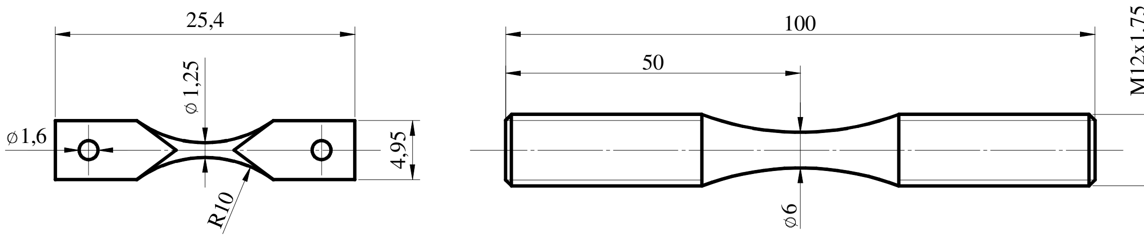


Fig. 7. Specimen geometry used in work [5]

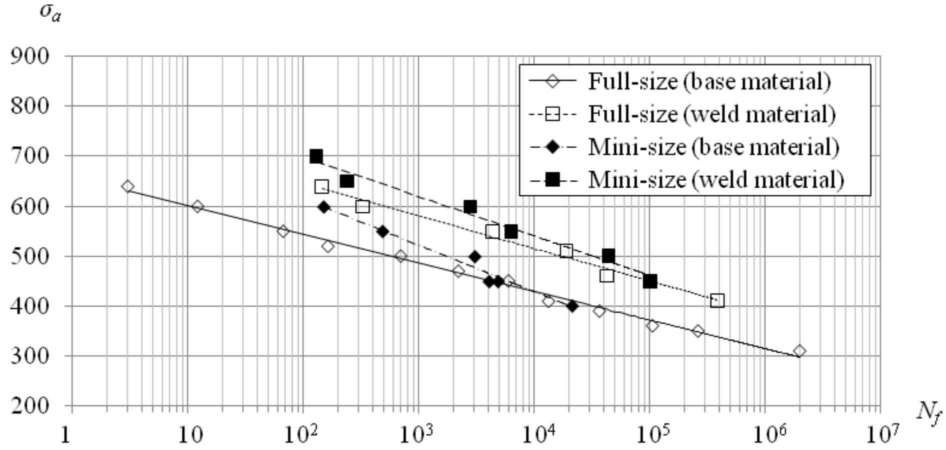


Fig. 8. Relation between stress amplitude and number of cycles [5]

The springboard for the authors of work [8] was the thought that machinery design more and more often focuses on miniaturization. With that in mind, it is indispensible to perform fatigue tests for the plants of real (small) dimensions. Work [8] presents the impact of the effect of scale on fatigue life of materials used in micro-machines (space satellites, medical care). As claimed by the authors of the work, the specimens are made from pure iron and pure aluminium (original names taken after work [8]) 0.2 mm, 0.3 mm and 0.6 mm in diameter. The electrolytic polishing apparatus was used. The test stand has been built from the electrodynamic actuator generating low stress amplitudes. The specimens were with axial loads. The pure aluminium specimens were independent of the diameter. For the same values of the stress amplitude the fatigue life was comparable, while the samples of a smaller diameter made from pure iron showed lower fatigue life.

Work [4] presents the impact of the size effect in the rotationally-bended specimens in the environment of high humidity (60%, 70%, 80%, 90%) and water at the temperature of 25°C. The tests will allow for the selection of materials of e.g. small parts of machines used in the robot driver shafts. The samples were made from steel SS400 and S45C, 8 mm (normative specimen), 2 mm and 1 mm in diameter (mini specimen), respectively. The surfaces of the specimens were polished with abrasive paper grade 1200 (emery paper). It was shown that in the environment of a high humidity the fatigue strength increases with a decrease in the specimen diameter (Fig. 9). In the case of smaller specimen diameters, the water molecules adhere to the surface more easily forming a layer. Water drops cause a faster initiation of corrosion and cracks than the water layer on the specimen surface.

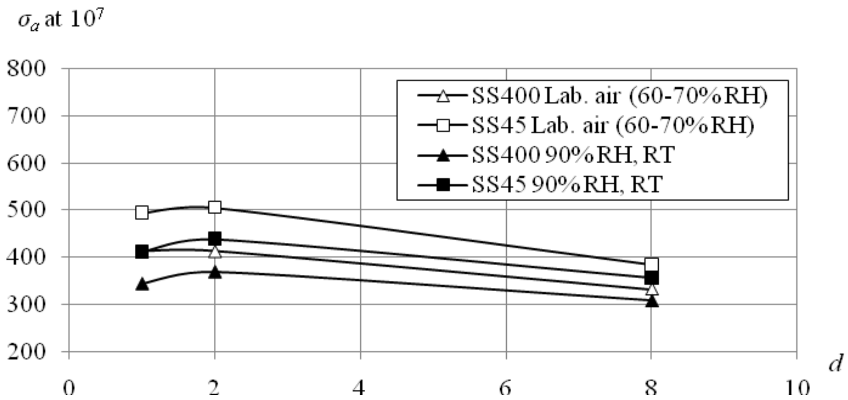


Fig. 9. Relation between fatigue strength at 10^7cycles and specimen diameter [4]

Research work [3] is of different nature; it presents the application of ultrasonic to research the fatigue life of high-strength steel. The main advantage of the use of ultrasonic is very high working frequency reaching 20 kHz, thanks to which reaching the number of cycles of 10^9 is possible within the time shorter than for the typical frequencies reaching 100 Hz. The tests were performed for the samples 8 mm, 7 mm, 3 mm (mini specimen) in diameter made from steel 40HMA (42CrMo4). The reference specimen was a normalised specimen 6 mm in diameter tested in the servo-hydraulic fatigue machine. The surface of the specimen was given its finish with the abrasive powder 1µm.

a)

b)

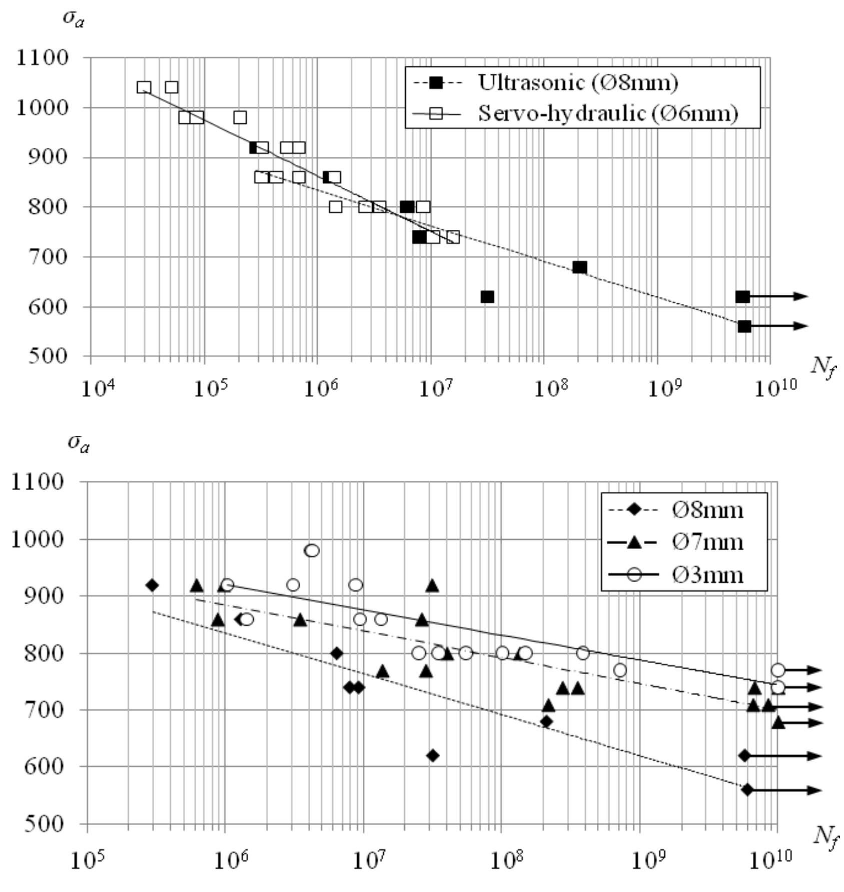


Fig. 10. Relation between stress amplitude and number of cycles:
a) ultrasonic loads and servo-hydraulic loads, b) specimen of different diameters [3]

In the ultrasonic fatigue tests the samples were cooled with the air to decrease the temperature increase. The tests were interrupted to maintain the specimen temperature on the surface not exceeding 30°C. The fatigue life obtained with the method using ultrasonic is similar to the fatigue life obtained on servo-hydraulic fatigue machine (Fig. 10a). There was observed an impact of the size effect. For the samples of lower diameter there were reported higher fatigue life values than the normalized specimens (Fig. 10b).

5. Conclusions

There is some state of knowledge on the size effect, including the model commonly considered the applicable one; it assumes that the size effect does not get identified in the range of samples the dimensions of which are below 7 ÷ 12 mm (depending on the source). Such state of knowledge is reflected in the recommended calculation models and their related dependences. The sample data come from literature where for the diameters from 1 mm to 7.5 ÷ 12 mm, depending on the material, the co-efficient of the size effect is defined at level 1. The application of the formula depending on the material of the element shows that the size effect depends on the material structure. In the case of materials of heterogeneous structure there is a greater sensitivity to the change of dimensions.

Work [7] provides interesting experimental results of the quantitative effect of the cross-section value, which shows clearly the justifiability of the statement of no size effect in a very narrow range. In general, the effect is also found in the range of the smallest diameters (1 ÷ 5 mm).

The impact of the size effect in the range of the smallest diameters is shown in the experimental studies referred to in item 5. It was experimentally proven that fatigue strength and life of mini specimens (1 ÷ 3 mm) are greater than the normative specimens (6 mm). Those works comply with the relationships presented following work [7] in Fig. 3. The present tests were performed when exposed to bending and tensile loads.

The work has formulated a hypothesis on the justifiability of searching for the test methodology and using mini specimens as a way to lower the costs of tests. With the review of the state of knowledge provided here, assuming the above reasoning as the major one, one shall note that the application of mini specimens is also justifiable due to:

- widening the scope of the possibilities of identifying the material characteristics when sampling a normative specimen is impossible (e.g. elements embossed from aluminium),
- using low values of displacements in the tests, which is favourable to the use of high frequencies and, as a result, shortens the test time,
- using low values of specimen of strain in the tests (on purpose due to selected material groups).

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