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THE EFFECT OF NODUL SIZE ON FATIGUE PROPERTIES OF FERRITIC NODULAR CAST IRON.

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ABSTRACT

The influence of size of spheroidal graphite particles on the fatigue properties of nodular cast iron is investigated. Sand cast nodular iron plate material has been used with different thicknesses with a full ferritic matrix structure. For the 2 mm plate, different surface conditions have been investigated. Fatigue limits have been determined with the staircase method. Using the square root area approach of Murakami and Endo, the theoretical results of the fatigue limits were compared with the experimental results. The calculation results show higher fatigue limits than the experimental results if the model only assumes the presence of nodules as defects. A better congruence is found when real defects are taken into account. The experiments show that the fatigue limit decreases with increasing nodul size.

INTRODUCTION

Nodular cast iron is a good material for industrial applications, especially since recent developments in the casting technology enabled the production of thin-walled nodular cast iron. The mechanical properties are similar to those of commonly used steels. An application area is the car industry for engine and safety components. The microstructure of nodular cast iron consists of spheroidal graphite nodules embedded in an iron matrix.

In this research fatigue properties of a ferritic nodular cast iron plate material have been investigated. Hereby the influence of amount and size of the nodules at the same carbon content on the fatigue properties has been determined. The fatigue limits have been determined at 4 million cycles for R=0,1 with the use of the staircase method. The theoretical results of the fatigue limits using the square root area approach of Murakami and Endo [1] were compared with the experimental results.

EXPERIMENTS

Three thicknesses, 2 , 4 and 7 mm, have been used with respectively about 6000, 1500 and 500 nodules per mm^2. The largest nodul sizes for the three thicknesses are about 14, 18 and 32 pm respectively. The same carbon content was applied for all thicknesses. The cast iron contains about 3.8% C, 2.9% Si, 0.04% Mn, and 0.6% Ni. In Figure 1 the metallographic structures of the 2, 4 and 7 mm thick nodular cast iron are shown. At first the fatigue limits at 4 million cycles at R=0,1 have been determined using the staircase method. The geometry of the tensile specimen for the fatigue limit tests complies with the ASTM standard

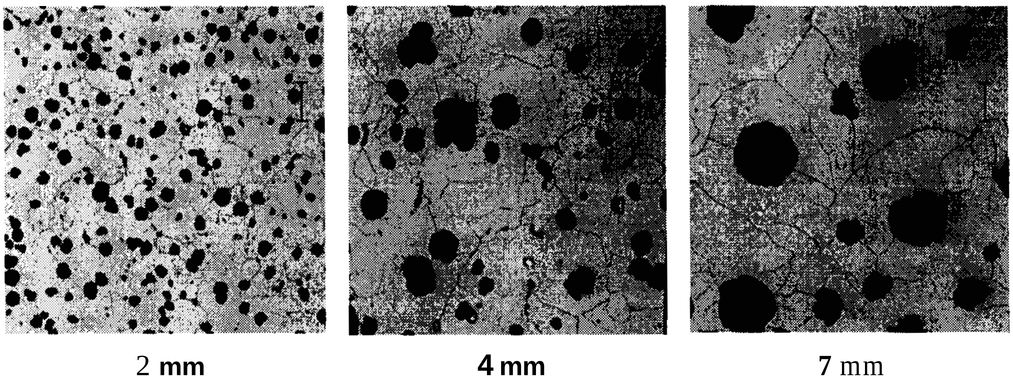

Figure 1: Metallographic structures of the investigated nodular cast iron (marker = 20 μm).

E 466-96 [2]. Earlier experiments showed crack initiation on the corner of the specimens with a thickness of 2 mm, although the machined side-surface was treated with a shot-peening treatment. An effort was made to promote initiation from the cast skin by rounding of the corners of the specimens (approximate decrease in area 2.5%). In order to investigate the influence of the cast skin (a source of defects) on fatigue properties, experiments were conducted with specimens without the cast skin. Figure 2 shows the surface geometry of the different 2 mm tensile specimens.

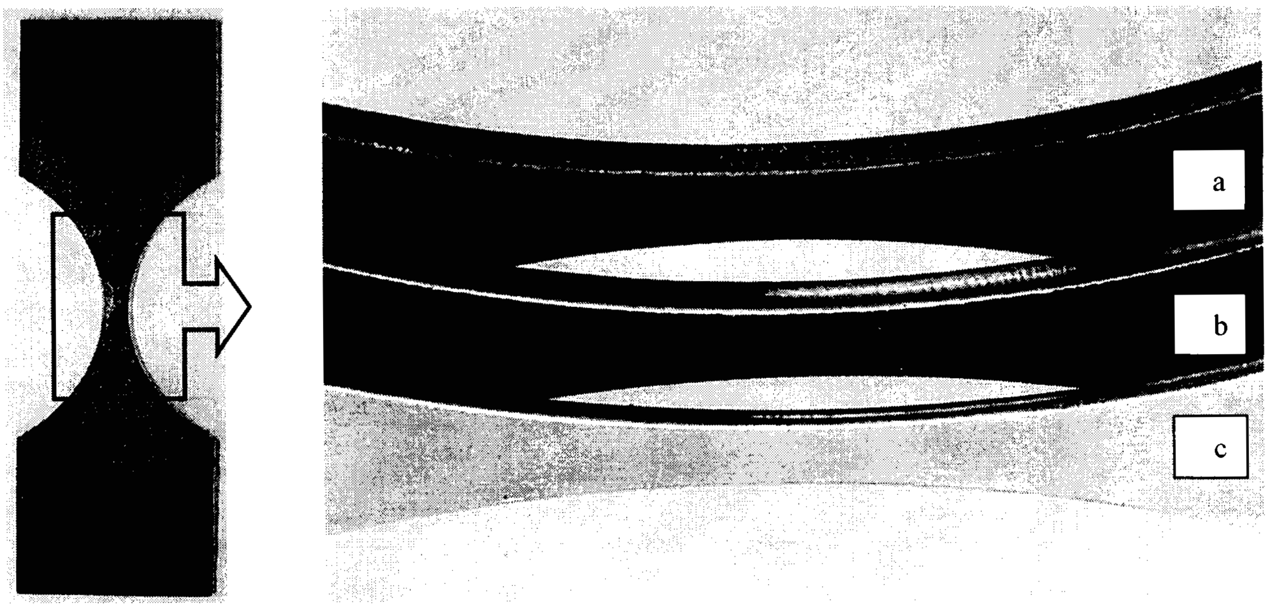

Figure 2: Different surface geometry's of the 2 mm tensile specimens (a: cast skin and shot-peened, b: cast skin and curved corners and c: without cast skin and with curved corners).

THEORY

Staircase method

The mean fatigue limit and standard deviation are estimated from:

$$\sigma_w = \sigma_0 + \Delta\sigma \cdot \left(\frac{A}{\Sigma p} \pm \frac{1}{2} \right) \tag{1}$$

$$S = 1{,}620 \cdot \Delta\sigma \cdot \left(\frac{B\Sigma p - A^2}{(\Sigma p)^2} + 0{,}029 \right) \tag{2}$$

where: +%is used if the number of broken specimens (n) > the number of unbroken specimens (u) and -% is used if n<u; further p=n if n<u and p=u if n>u; σ_w=fatigue limit stress; σ_0=lowest stress level; $\Delta\sigma$=stress step; $A = \Sigma i p_i$; $B = \Sigma i^2 p_i$; S=standard deviation.

The square root area parameter model

The square root area parameter model was introduced by Murakami and Endo [1]. The parameter √area is defined as the square root of the projected area of a defect or crack on a plane perpendicular to the maximum tensile stress. They proposed equations for the threshold for fatigue crack growth AK,,,and the fatigue limit σ_w for internal and surface defects:

$$AK_{,,,} = 3{,}3 \cdot 10^{-3} \cdot (HV + 120) \cdot \left(\sqrt{area}\right)^{1/3} \cdot [(1-R)/2]^{\alpha} \tag{3}$$

where α=0,226+HV·10^{-4} . Using:

$$K = 0{,}650 \cdot \sigma \quad \cdot \sqrt{\pi\sqrt{area}} \tag{4}$$

for a surface defect, the fatigue limit is:

$$\sigma_w = 1{,}43 \cdot (HV + 120) \cdot \left(\sqrt{area}\right)^{-1/6} \cdot [(1-R)/2]^{\alpha} \tag{5}$$

For an internal defect it is:

$$\sigma_w = 1{,}56 \cdot (HV + 120) \cdot \left(\sqrt{area}\right)^{-1/6} \cdot [(1-R)/2]^{\alpha} \tag{6}$$

The influence of the material matrix structure is accounted for by HV the Vickers hardness. For nodular cast iron it is difficult to estimate the hardness of the matrix. **A** number of nodules will always influence the outcome of a hardness measurement. Endo [4] introduced a correction to enable determination of the matrix hardness:

$$HV = \frac{HV_n}{(1-f_n)} \tag{7}$$

where HV,, is the mean hardness of matrix and nodules and f_n the porosity, i.e. the volume fraction of the nodules (graphite):

$$f_n = \frac{V_C}{V_{tot}} \tag{8}$$

with:

$$V_C = \frac{\rho_{Fe} \cdot V_{tot} - m_{tot}}{\rho_{Fe} - \rho_C} \tag{9}$$

ρ_{Fe} and **p,** are the densities of carbon and iron respectively, m_{tot} is the total mass, and V,,, and V, are the total volume and the volume of the carbon respectively.

RESULTS AND DISCUSSION

Measured Fatigue limits

Results of tests at 4 million cycles are shown in figure **3** for different types of specimens with 2 mm thickness. Although the specimens with 2 mm thickness of earlier experiments were shot- peened, they all

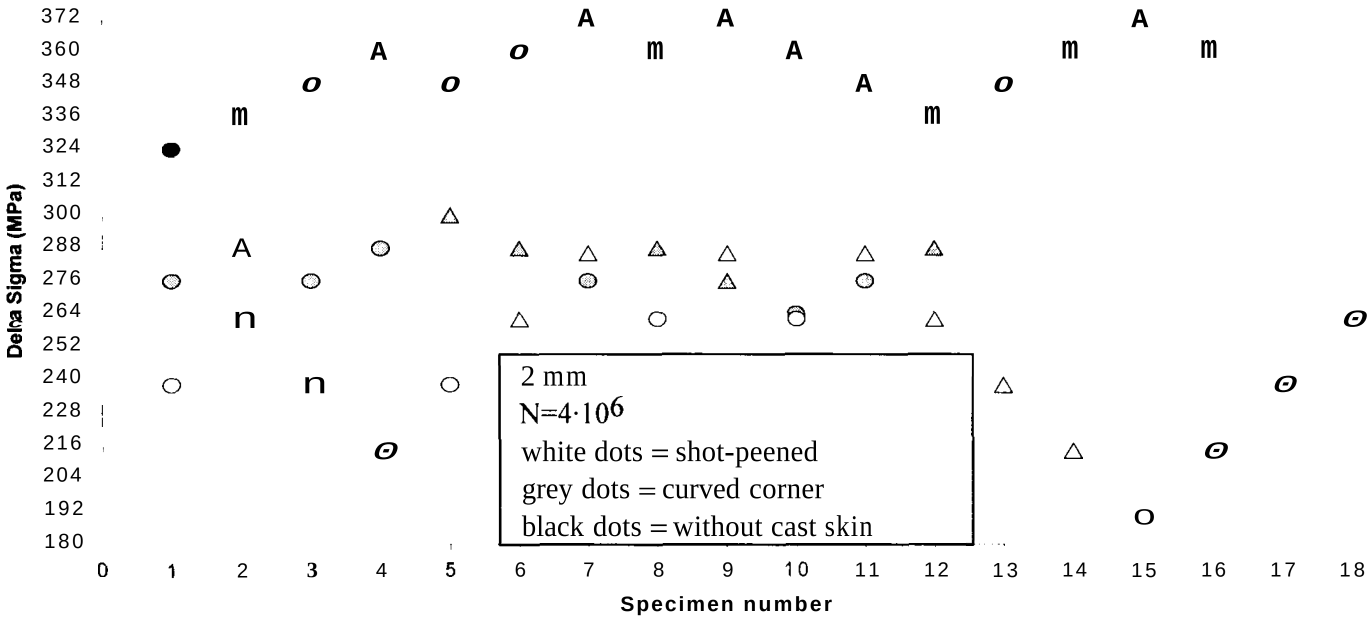

Figure 3: Staircase results of the 2 mm specimens, R=0.1.

showed initiation from the corner of cast skin and machined side. The shot-peening had more effect on the 4 mm and 7 mm thick specimens. For the specimens with 2 mm thickness, this resulted in a lower ***c,*** compared to the results with initiation from the cast skin. The curved corners promoted initiation from the cast skin; only one out of twelve specimens showed initiation from the corner (figure 4). Even higher values for ***c,*** were found when the cast skin was removed by machining (one out of seven specimens showed initiation from the corner). A summary of the results for the fatigue strength is shown in Table 1. In this table σ_w is the stress amplitude at R=0,1.

TABLE 1
FATIGUE LIMITS AND STANDARD DEVIATIONS FOR R=0,1

Thickness (mm)	σ_w (MPa) staircase $N=4\cdot10^6$ cycles
2, shot-peened	105.5 ± 29.4
2, curved corners	144.6 ± 3.6
2, without cast skin, curved corners	183.6 ± 5.9
4, shot-peened	126.3 ± 6.8
4, shot-peened, without cast skin	161.2 ± 2.8
7, shot-peened	121.0 ± 7.9

Using a Smith (Goodman) diagram, the fatigue limits can be calculated (by linear extrapolation) for different R-values. Figure 5 shows the Smith diagram for 2 mm nodular cast iron with curved corners. The fatigue limit for mean stress zero (R=-1) is found by extrapolation from the value at R=0,1. The fatigue limit is about 210 MPa. An experimentally determined σ_{UTS} of 574 MPa was used for the calculations. Table 2 shows the extrapolation results for different thicknesses using the Smith diagram. A problem exists in using linear extrapolation. For example: the fatigue limit for 2 mm thickness with cast skin and rounded corners is 144.6 MPa for R=0.1. If the Smith diagram is applied a value of 208.9 MPa is found for R=-l (figure 5). However, if the surface defect size is calculated which gives a fatigue limit of 144.6 at R=0.1, a square root area of 798 pm is found. If the fatigue limit is then calculated for R=-l and using this defect size, a value of 176 MPa is found instead of 208.9 MPa.

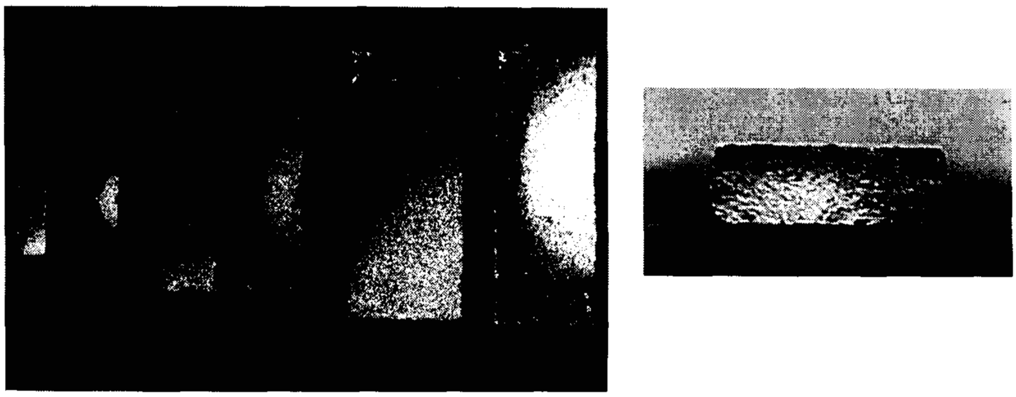

Figure 4: Fatigue fracture surfaces (of 2, 4 and 7 mm specimens) initiated from the cast skin and from a corner (left) and fatigue crack initiation from a cast skin surface of 2 mm thickness with curved corners (right).

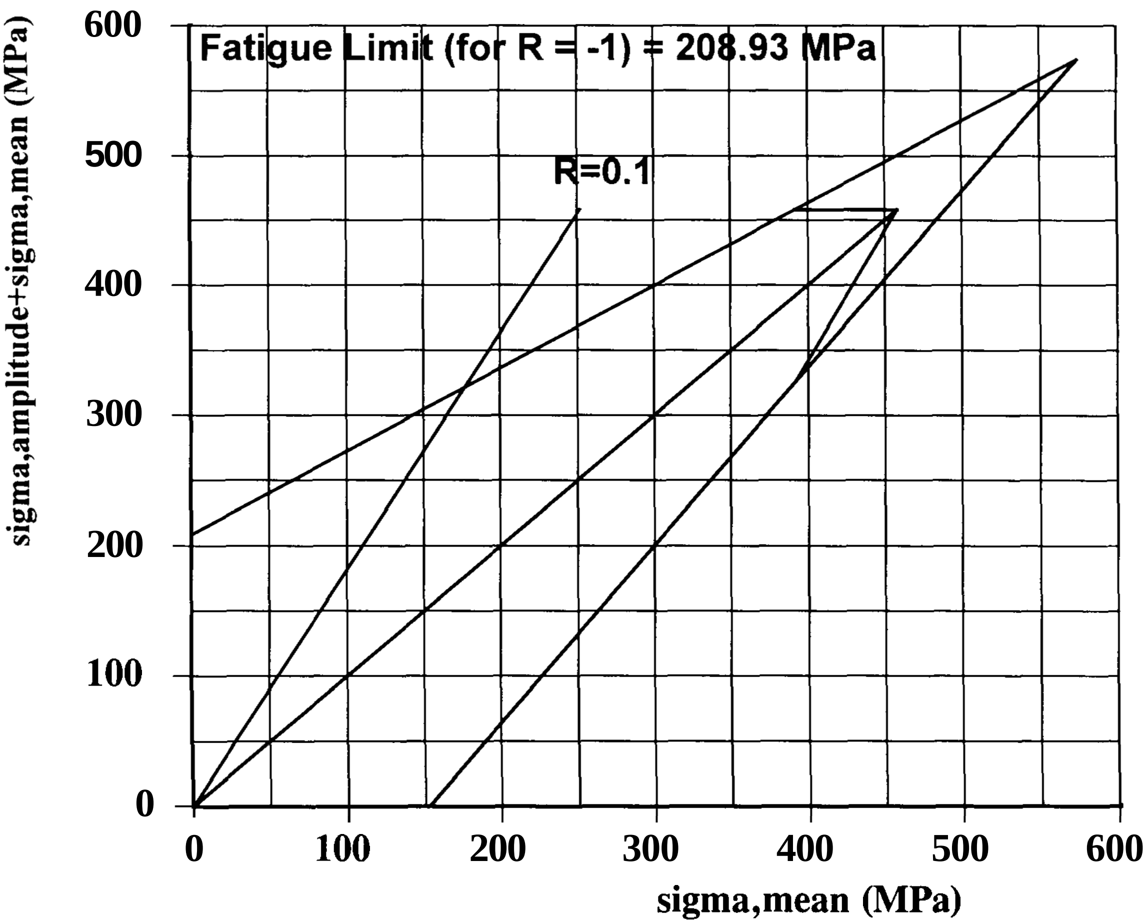

Figure 5: Smith diagram of 2 mm thick cast iron specimens with cast skin and curved corners, the line for R= 0,1 is shown.

Calculation results using the model of Murakami and Endo

The calculation results have also been given in table 2, using eq. (6) for internal defects with the nodul sizes as a measure. In the table two results are shown; the first is based on the nodul size (figure l), the second on the real defect size as found in the initiation area of crack growth on the cast skin of the specimens (figure 6). For the nodul based calculation eq.(6) is used, for the surface defect eq.(5). The mean $\sqrt{area}$ of the surface defects are 142 pm for 2 mm thickness and 640 pm for 4 mm thickness. No initial defect size could be measured for 7 mm. The Vickers hardnesses HV (kgf/mm^2) were 255,208 and 187 for 2,4 and 7 mm thickness respectively. The nodul size correction, eq.(7), was used.

TABLE 2
FATIGUE LIMITS (MPa) FOR R=0.1 (MEASURED OR CALCULATED) AND R= -1 (CALCULATED OR EXTRAPOLATED), σ_{UTS}=574 MPa, σ_{ys}=458 MPa

Thickness (mm) s-p=shot-peened c-c=curved corners	Experiments R= 0,1	experiments extrapolated R=-1	calculated R=0.1 nodul	calculated R=-1 nodul	calculated R=0.1 real defect	calculated R=-1 real defect
2, s-p	105.5 ± 29.4	135.3	315	384	192	235
2, c-c	144.6 ± 3.6	207.8	315	384	192	235
2, c-c no skin	183.6 ± 5.9	300.2	315	384	192	235
4, s-p	126.3 ± 6.8	172.3	265	322	131	160
4, s-p no skin	161.2 ± 2.8	245.2	265	322	131	160
7, s-p	121.0 ± 7.9	163.1	226	274		

The calculated values of the fatigue limit σ_w for the real measured defects have the same order of magnitude as the experimentally found values. However it should be noted that the initial defect sizes were only measured for a few specimens. Besides that, they were measured on fracture surfaces of specimens that failed before the 4 million cycles were reached. Specimens which lasted more than 1 million cycles were chosen. There is a large difference with the calculated values based on the nodul size. The nodul based calculation gives an indication about the theoretical fatigue limit for a cast iron with defects smaller than the nodul sizes. The theoretical improvement of the fatigue limit can be as high as almost 200% compared with the real experimental results. Tests without the cast skin show values of 183,6 MPa for the fatigue limit.

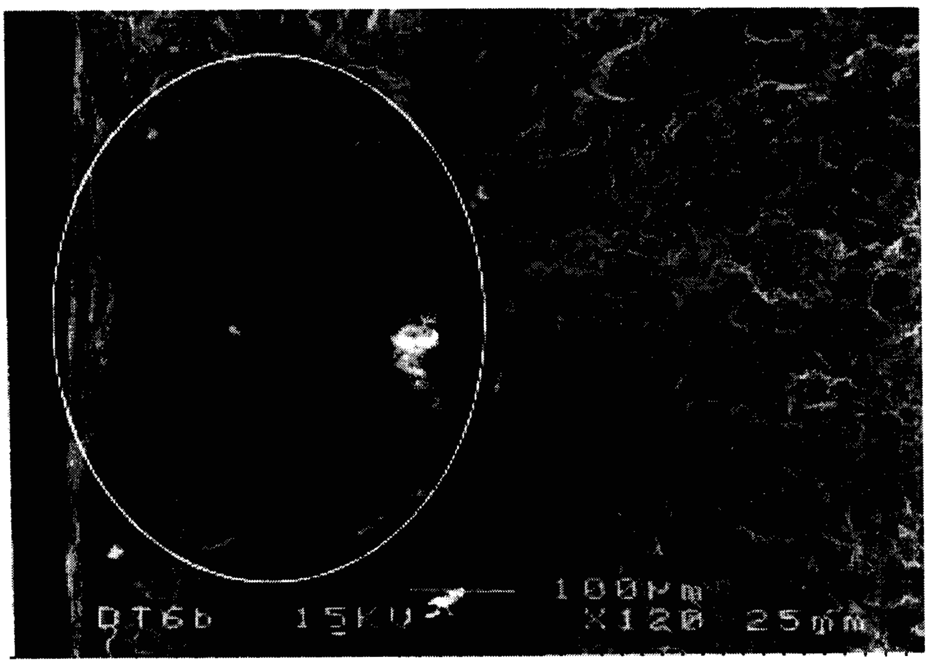

Figure 6: Initiation area of crack growth near the cast skin of a 4 mm specimen.

This value is still below σ_w found with calculated values using the nodule size as defect, implying the presence of internal defects slightly larger than the nodules. For a fatigue limit of 184 MPa a large internal defect size of about 300 pm is expected, or it might be that a cluster of nearby interacting noduls results in a comparable defect and hence in such a lower fatigue limit.

CONCLUSIONS

When initiation takes place from the cast skin, higher fatigue limits are found then when initiation starts at a corner of the cast skin. Also the value of the fatigue limit gives a better representation of the fatigue limit of the material when initiation starts on the cast skin. However a decrease in standard deviation is found when cracks are initiated from the cast skin.

Higher values of the fatigue limit are found when the cast skin is removed by machining. Further research should be conducted on specimens with 7 mm thickness.

The calculation model of Murakami and Endo gives ***higher*** fatigue limits than the experimental results if the model only assumes the presence of nodules as defects. When real initial defects on the cast skin are taken into account the difference between experiment and calculation becomes much less.

SYMBOLS USED

a	= half crack length (mm)	P	= load (kN)
f	= frequency (Hz)	R	= load ratio = P_{min}/P_{max}
K	= stress intensity factor (MPa$\sqrt{m}$)	t	= specimen thickness (mm)
N	= number of cycles	w	= specimen width (mm)

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