

FATIGUE CRACK PROPAGATION RATES AND THRESHOLD STRESS INTENSITY FACTORS IN HIGH STRENGTH LOW ALLOY STEEL PLATE, BAR AND FORGINGS

1. NOTATION

a	crack length, crack half-length or crack depth	m	in
C	coefficient for linear interpolation of crack growth rate curve defined by $da/dN = C(\Delta K)^n$	$m\left(\frac{m^{3/2}}{N}\right)^n$	$in\left(\frac{in^{3/2}}{lb\,f}\right)^n$
f_p	0.2 per cent proof stress of material	N/m ²	lb f /in ²
f_t	tensile strength of material	N/m ²	lb f /in ²
K	stress intensity factor	N/m ^{3/2}	lb f /in ^{3/2}
ΔK	stress intensity factor range	N/m ^{3/2}	lb f /in ^{3/2}
K_{Ic}	plane strain fracture toughness in Mode I	N/m ^{3/2}	lb f /in ^{3/2}
ΔK_{TH}	threshold stress intensity factor range	N/m ^{3/2}	lb f /in ^{3/2}
N	number of load cycles		
n	slope of crack growth rate curve		
R	S_{min}/S_{max}		
S	stress based upon cross-sectional area of specimen	N/m ²	lb f /in ²
S_{max}	maximum value of S in fatigue cycle	N/m ²	lb f /in ²
S_{min}	minimum value of S in fatigue cycle	N/m ²	lb f /in ²
α	geometrical factor in stress intensity factor		

1.1 Conversion Factor

Both SI and British units are shown in the notation. The data are presented in terms of SI units and the following conversion factor for British units applies.

$$1 \text{ MN/m}^{3/2} = 910.047 \text{ lb}\,f/\text{in}^{3/2}.$$

Note also that,

$$1.0 \text{ MN/m}^{3/2} = 1.0 \text{ MPa m}^{1/2} = 31.6228 \text{ N/mm}^{3/2} \text{ (that is, } 10^{3/2} \text{ N/mm}^{3/2}\text{)}.$$

2. NOTES

2.1 General

This Item presents fatigue crack propagation rate data in the range 10^{-4} to 10^{-11} m/cycle, (4×10^{-3} to 4×10^{-10} in/cycle) and also threshold stress intensity factors, ΔK_{TH} , in terms of linear elastic fracture mechanics, as described in Item No. 80036*. Data are presented on the rate of growth of fatigue cracks in high strength ($f_t > 850 \text{ MN/m}^2$) low alloy steel plate, bar and forgings. A low alloy steel is here defined as a steel where the contribution (by weight) of any particular alloying element is less than 5 per cent. The chemical composition and mechanical properties of the materials are given in Table 7.1.

2.2 Presentation of data

Figures 1 to 22 provide curves of crack propagation rate, da/dN , plotted against the stress intensity factor range, ΔK , for each of the material designations. The curves have been drawn through the means of the data for various values of stress ratio, R . Tables containing mechanical properties and crack growth data appear on the pages facing the relevant figures.

Figures 23 to 25 present the effect of the change of R on crack growth rate for three ranges of 0.2 per cent proof stress. Figure 26 summarises the curves and the effect that change of R and different 0.2 per cent proof stresses have on crack growth rate.

2.3 Test conditions

The data are derived from constant amplitude fatigue tests on specimens of various standard types. The thicknesses of the specimens are given, where known, in the tables accompanying Figures 1 to 22. The tests were conducted in laboratory air unless otherwise stated, at room temperature, and at loading frequencies in the range 0.1 to 175 Hz, with the exception of the tests reported in Derivation 26 which were conducted at 375 Hz.

The majority of the tests were stated to be conducted within the framework of linear elastic fracture mechanics, implying that the stress across the remaining ligament of the specimen did not exceed the yield strength of the material and that the plastic zone size was small compared with the crack length (see Section 1 of Item No. 80036).

2.3.1 Fracture toughness testing

Some of the materials for which data are presented in this Item were also subjected to fracture toughness tests. The values of the critical stress intensity factors obtained from these tests are indicated on the figures and these values are designated K_{IC} . Values of K_{IC} for these and other steels at other temperatures and with different heat treatments may be found in Item No. 83023†.

2.4 Determination of fatigue threshold (ΔK_{TH})

Certain derivations quoted threshold values of stress intensity factor range (ΔK_{TH}) (that is the value of ΔK below which fatigue cracks will not grow). A common definition of ΔK_{TH} is the maximum value of ΔK at which no detectable crack growth occurs in 10^7 cycles. The values of ΔK_{TH} are considered to be valid if the crack growth rate curves are vertical or very nearly vertical. Since a crack extension of less than

* Data Item No. 80036, "Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

† Data Item No. 83023, "Fracture toughness (K_{IC}) values of some steels".

10^{-4} m (4×10^{-3} in) would remain undetected by conventional crack length monitoring equipment, testing for 10^7 cycles implies a minimum growth rate of 10^{-11} m/cycle (4×10^{-10} in/cycle). This corresponds to an average growth rate of about one quarter of a lattice spacing per cycle.

The method most frequently used in the derivations for determining very low rates of crack propagation near the threshold was the load reduction (or load shedding) technique. This involved reducing the load, usually in increments of less than 10 per cent, between sets of measured crack extension and load cycles, until no further crack extension could be detected in 10^7 cycles.

In the tests, at each cyclic load level, before crack measurements were taken, the crack was grown until it was several times longer (usually 3 to 5 times) than the maximum plastic zone size produced at the previous load level. This procedure was designed to reduce the effects of stress history, but cannot be continued for a crack that has ceased to propagate. At that point in the test, however, the plastic zone size was considered to be negligible.

3. DISCUSSION OF DATA

3.1 Method of Analysis of Test Data

Data were provided in the derivations in the form of curves of da/dN against ΔK . Equation (4.2) of Item No. 80036 defines ΔK as

$$\Delta K = (S_{max} - S_{min})(\pi a)^{1/2} \alpha. \quad (3.1)$$

All the data analysed in this Item have been obtained from da/dN and ΔK data given in the derivations. The values of α in Equation (3.1) that were used in the derivations were values appropriate to the loading conditions and geometry of the specimens tested. Allowances for the effects of plasticity at the crack tip on the value of ΔK were not made except for the data obtained from Derivations 16 and 20.

3.2 Effect of fracture toughness

In this group of materials those steels having low values of fracture toughness, ($< 50 \text{ MN/m}^{3/2}$) tend to have higher crack propagation rates for given values of ΔK and also have steeper crack growth rate curves than materials having medium to large values of fracture toughness. The steepness of the crack propagation rate curve is indicated by the value of n , used in Equation (4.1) (see Section 4.1).

3.3 Effect of mean stress

The effect of mean stress is presented in terms of the stress ratio R . In some cases the value of R used was not held constant during the test, or its value was not stated. The effect of stress ratio R on fatigue crack propagation rate was more pronounced at low values of stress intensity near ΔK_{TH} and at high values of stress intensity near K_{Ic} . This effect can be seen from the summary curves, Figures 23 to 25, which show that an increase in stress ratio R leads to an increase in crack propagation rate da/dN for a given value of ΔK .

3.4 Variation with material proof stress

From Figure 26 it can be seen that an increase in 0.2 per cent proof stress leads to an increase in crack propagation rate for a given value of ΔK . However, the effect is less pronounced at low values of stress ratio R and low values of crack propagation rate da/dN . This is the opposite effect to that presented in Item

No. 81011* for lower strength low alloy steels where $f_t < 850 \text{ MN/m}^2$.

3.5 Effect of frequency and environment

The effect of the different frequencies of the loading cycle on crack propagation rate has not been investigated. It is generally thought that crack propagation tests conducted at low frequencies of loading ($< 10 \text{ Hz}$) in corrosive environments will produce different crack growth rates from tests conducted in air at room temperature.

4. CALCULATION OF CRACK GROWTH LIFE

4.1 Use of curves

As described in Item No. 80036, integration over a selected portion of the crack growth rate curves, Figures 1 to 22 of this Item, will lead to an estimate of the total crack growth and associated number of cycles. In the absence of any suitable equation to cover the full range of da/dN , the complete curves available from the data are presented. Values read from these curves are suitable for use in computer programs that predict crack growth life; the accuracy of such predictions will be dependent on the number of values provided. Alternatively, the slope of a straight portion of the curve, or a mean straight line representing a portion of a curve, may be represented by the characteristic n so that over discrete ranges of the curves, which may be reasonably considered straight on a logarithmic presentation, the expression

$$\frac{da}{dN} = C(\Delta K)^n \quad (4.1)$$

is applicable (see Reference 36). This simple law can be analytically integrated to obtain the total crack growth life. The value of n may be calculated from any two co-ordinates $((da/dN)_1, (\Delta K)_1)$ and $((da/dN)_2, (\Delta K)_2)$ using the following equation.

$$n = \frac{\log \left[\frac{(da/dN)_2}{(da/dN)_1} \right]}{\log \left[\frac{(\Delta K)_2}{(\Delta K)_1} \right]} \quad (4.2)$$

The value of C is then found by inserting n , together with one set of co-ordinate values, into Equation (4.1). For convenience, suggested values of n and C , obtained from the mean crack propagation rate curves for various ranges of da/dN , are given in the tables accompanying Figures 1 to 22.

When calculating the fatigue crack growth life of a component using the straight line law of Equation (4.1), in preference to performing a step-by-step integration procedure, the values of da/dN and ΔK used in the calculation of n and C should correspond to points along the straight line approximation rather than being obtained directly from the fatigue crack propagation rate curves.

* Data Item No. 81011 "Fatigue crack propagation in low and medium strength low alloy steel plate, bar and forgings".

5. DERIVATION AND REFERENCES

5.1 Derivation

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5.2 References

The references given are recommended sources of information supplementary to that in this Item.

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6. EXAMPLES

6.1 Example 1

A structural steel plate 300 mm (11.8 in) wide by 6 mm (0.24 in) thick manufactured from BS 970, 817 M40 (EN 24) steel is found to have a central crack through its thickness. When first observed the crack has a half-length of 5 mm (0.2 in); it is required to know the mean number of load cycles that can be applied before the maximum crack half-length that can be tolerated, that is, 25 mm (1 in), is reached. The tensile fatigue loading on the plate is 0–120 MN/m² (0–17 400 lbf/in²), the 0.2 per cent proof stress of the material is 1200 MN/m² (174 000 lbf/in²) and $K_{Ic} = 95 \text{ MN/m}^{3/2}$ (86 500 lbf/in^{3/2}).

The number of load cycles used to reach the maximum acceptable crack half-length will be calculated by integrating Equation (4.1). The values of n and C used in Equation (4.1) are taken from the table accompanying the appropriate figure, in this case Figure 5. Since no data are available for the precise values of R and f_p occurring in the problem, namely 0 and 1200 MN/m² (0 and 17 400 lbf/in²), a conservative approach would be achieved by using, from the data available, the nearest values greater than these, namely $R = 0.17$ and $f_p = 1275$ MN/m² (185 000 lbf/in²). Geometry effects will be considered and for this case the equation for α is given by

$$\alpha = \left(1 - (a/b)^{1.8}\right)^{-0.54} \quad (6.1)$$

Equation (6.1) is obtained from Reference 38 and is a “closed form” solution which may be readily integrated and lies within 2 per cent of the more generally quoted polynomial solutions for a central crack in a finite plate under tensile loading. No allowance for plasticity will be made in this example.

Using Equation (3.1) to calculate the initial and final values of ΔK gives

$$\begin{aligned} \Delta K_1 &= 120(\pi \times 0.005)^{1/2} \left(1 - (0.005/0.15)^{1.8}\right)^{-0.54} \\ &= 15.1 \text{ MN/m}^{3/2} \text{ (13 740 lbf/in}^{3/2}\text{)} \end{aligned}$$

and

$$\begin{aligned} \Delta K_2 &= 120(\pi \times 0.025)^{1/2} \left(1 - (0.025/0.15)^{1.8}\right)^{-0.54} \\ &= 34.4 \text{ MN/m}^{3/2} \text{ (31 300 lbf/in}^{3/2}\text{)}. \end{aligned}$$

From the appropriate table accompanying Figure 5 the values of C and n for the range 10^{-8} to 10^{-7} m/cycle can be seen to be $4.4 \times 10^{-12} \text{ m} \left(\frac{\text{m}}{\text{MN}}\right)^{3/2}$ and 3.0 respectively.

Equation (3.1) may be substituted into Equation (4.1) to give

$$\frac{da}{dN} = C \left((S_{max} - S_{min}) (\pi a)^{1/2} \alpha \right)^n \quad (6.2)$$

This equation may be re-written as

$$\frac{da}{dN} = CQ (a^{1/2} \alpha)^n \quad (6.3)$$

where

$$Q = C[(S_{max} - S_{min}) \pi^{1/2}]^n \quad (6.4)$$

so that, in this, case $Q = (120 \pi^{1/2})^{3.0} = 9.622 \times 10^6 (\text{MN/m}^2)^{3.0}$.

For the general case Equation (6.3) may be expressed as an integral with limits a_1 and a_2 and N_1 and N_2 thus

$$\frac{1}{CQ} \int_{a_1}^{a_2} \left(\frac{a^{1/2}}{\alpha}\right)^n da = \int_{N_1}^{N_2} dN. \quad (6.5)$$

Substituting into Equation (6.5) for α from Equation (6.1) yields

$$\frac{1}{CQ} \int_{a_1}^{a_2} \left(a^{-1/2} \left(1 - (a/b)^{1.8} \right)^{0.54} \right)^n da = \frac{1}{CQ} \int_{a_1}^{a_2} \frac{\left(1 - (a/b)^{1.8} \right)^{0.54n}}{a^{n/2}} da = \int_{N_1}^{N_2} dN. \quad (6.6)$$

Expanding the left-hand side of Equation (6.6) and noting that the right-hand side of the equation becomes ΔN (because the origin of the line given by Equation (4.1) is unknown and therefore individual values of N have no meaning) and using Maclaurin's series and integrating term by term for three terms the solution becomes

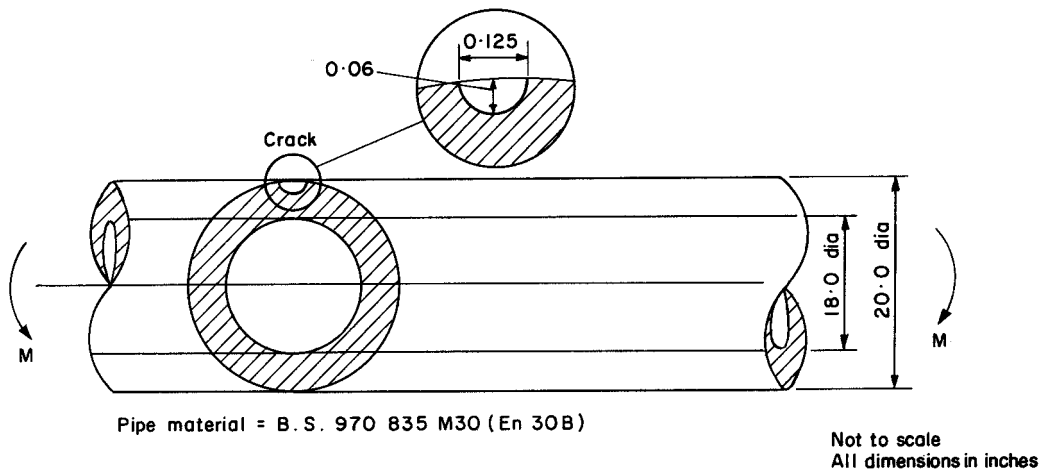
$$\frac{b^{(1-n/2)}}{1.8CQ} \left(\frac{a}{b} \right)^{(1-n/2)} \left[\frac{1}{\left(\frac{2-n}{3.6} \right)} - 0.54n \left(\frac{a}{b} \right)^{1.8} \left[\frac{1}{1 + \left(\frac{2-n}{3.6} \right)} - \left(\frac{(0.54n-1) \left(\frac{a}{b} \right)^{1.8}}{2} \right) \right] \right. \\ \left. \left(\frac{1}{2 + \left(\frac{2-n}{3.6} \right)} - \frac{(0.54n-2) \left(\frac{a}{b} \right)^{1.8}}{2} \right) \right] \Bigg|_{a_1}^{a_2} = \Delta N. \quad (6.7)$$

Substituting into Equation (6.7) the appropriate values, $a_1 = 0.005$ m, $a_2 = 0.025$ m, $b = 0.15$ m and the values of C , n and Q previously determined, the number of load cycles to reach the maximum acceptable crack half-length is given:

$$\Delta N = 369\,000 \text{ cycles.}$$

6.2 Example 2

During inspection of a pipe run a surface crack was discovered. Further ultrasonic investigation revealed the crack to be approximately semi-circular in shape, having a width ($2a$) of 0.125 in (3.18 mm) and a depth (c) of 0.06 in (1.52 mm). The configuration of the crack, and details of the pipe are shown in Sketch 6.1 below.



Sketch 6.1 Details of crack and pipe

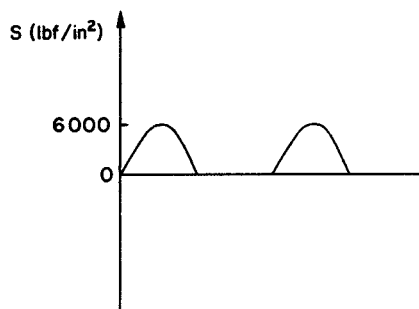
It is required to know if the crack is likely to propagate under the constant amplitude applied loading which is estimated to give an alternating axial stress of $\pm 6000 \text{ lbf/in}^2$ ($\pm 41.4 \text{ MN/m}^2$) at the crack position.

The solution to the problem involves establishing whether or not the combination of the existing crack, and loading cycle, gives rise to a value of ΔK that is greater than the threshold ΔK for the material. In practice the required data in terms of complete crack growth rate curves are not always available. Under these circumstances assumptions have to be made as illustrated in this example.

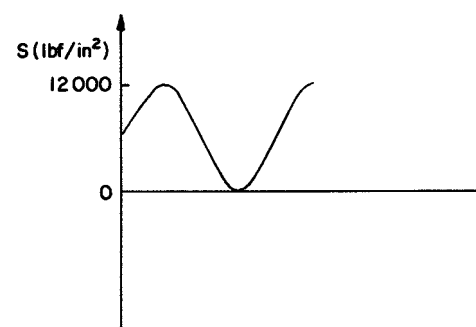
The curve of da/dN against ΔK for the material, EN 30B is shown in Figure 7. From this figure it will be noted that no threshold data are available. In this case the appropriate summary curve for materials having similar 0.2 per cent proof stresses must be consulted. Since f_p for EN 30B is given in the table accompanying Figure 7 as $196\,000 \text{ lbf/in}^2$ (1351 MN/m^2), the summary curve given in Figure 25 is appropriate, covering the range of 0.2 per cent proof stresses from $185\,000$ to $240\,000 \text{ lbf/in}^2$ (1275 to 1650 MN/m^2).

For this problem
$$R = \frac{S_{min}}{S_{max}} = \frac{-6000}{6000} = -1.$$

Figure 25 does not provide data for $R = -1$. However, data for $R = 0$ are available from which the value of ΔK_{TH} can be read off as $3650 \text{ lbf/in}^{3/2}$ ($4 \text{ MN/m}^{3/2}$). To compare the present loading cycle with those data given for $R = 0$, an assumption could be made to consider only the tensile part of the loading cycle and neglect the compressive part; this assumes that during compression the crack is closed and hence no crack growth occurs. This loading cycle is illustrated in Sketch 6.2. This assumption leads to errors since it does not take into account crack closure effects which have been demonstrated to contribute to crack growth. Alternatively, to consider the whole loading cycle in the calculation of ΔK , as illustrated in Sketch 6.3, leads to an over-conservative result. As an assessment of the present problem however it represents a sensible first estimate.



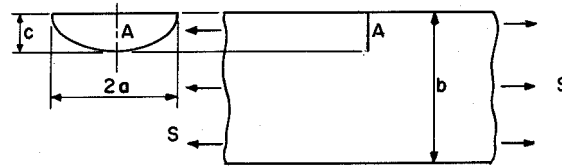
Sketch 6.2



Sketch 6.3

The value of α must now be estimated.

Figure 186 of Reference 37 gives values of K_I/K_0 where $K_0 = S(\pi c)^{1/2}$, for a semi-elliptical edge crack in a slab subjected to a uniform uniaxial tensile stress, as shown in Sketch 6.4.



Sketch 6.4

To make use of these curves in the solution of the present problem it is necessary to assume that the curvature effect of the pipe on α is small. This is considered valid, in this case, since the crack size is small in relation to the pipe outside diameter.

$$\Delta K = (S_{max} - S_{min})(\pi a)^{1/2} \alpha$$

and the critical value of a representing threshold can be established thus,

$$\Delta K_{TH} = 3650 = (6000 - -6000)(\pi a)^{1/2} \alpha .$$

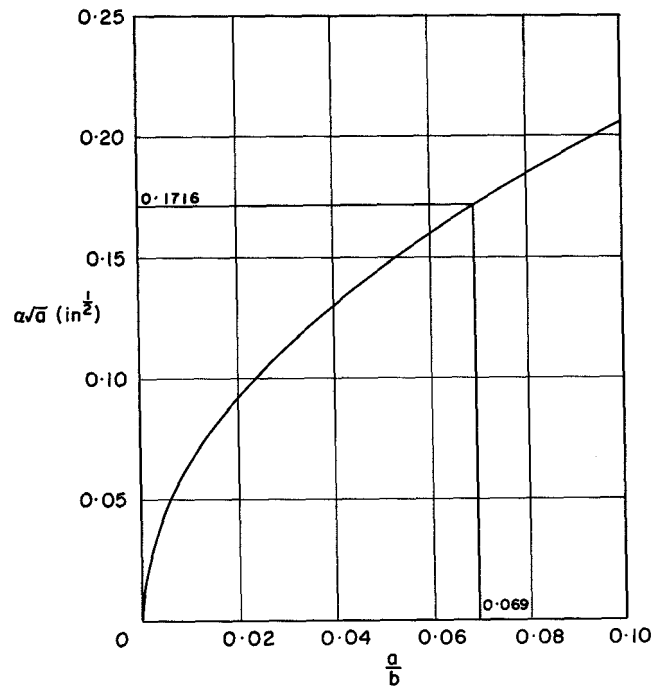
Hence $(a)^{1/2} \alpha = 0.1716 \text{ in}^{1/2} .$

In order to solve for the value of a corresponding to threshold, it is necessary to construct a cross plot of $(a)^{1/2} \alpha$ against a/b ; this is shown in Sketch 6.5. From this figure the value of a/b corresponding to $(a)^{1/2} \alpha = 0.1716$ can be read off as 0.069.

Hence a (corresponding to threshold) = $0.069 \times 1 = 0.069 \text{ in}.$

Therefore $2a = 0.138 \text{ in (3.5 mm)}.$

Since the measured value of a is less than that corresponding to the threshold condition, and since a conservative approach has been adopted, the present crack is unlikely to propagate. If, however, the measured crack length had been greater than that corresponding to the threshold condition, the assumptions made here, particularly with regard to loading cycle, should be re-assessed to obtain a more precise analysis.



Sketch 6.5 $\alpha\sqrt{a}$ against $\frac{a}{b}$

7. TABLES AND FIGURES

TABLE 7.1 Index of Materials for which Data are provided and their Chemical Compositions

Material designation	Notes	Figure No.	Composition (weight per cent), specification min/max or specimen values									
			C	Si	Mn	Ni	Cr	Mo	S	P	V	Other
AISI 4140		1	0.42	0.32	0.96	0.24	0.99	0.23	0.013			
AISI 4330		2	0.28	0.20	0.75	1.65	0.75	0.35			0.05	
AISI 4340		3	0.33	0.35	1.00	2.00	1.00	0.5	0.04	0.04	0.10	
			0.4	0.33	0.7	1.72	0.89	0.22	0.022	0.008	0.074	
			0.4		0.72	1.71	0.80	0.25	0.023	0.025		
			0.42	1.59	0.76	1.76	0.76	0.41	0.002	0.007	0.1	
(300-M)			0.38	0.25	0.85	1.7	0.76	0.25	0.016	0.006		
(Mil-S-5000)			0.43	0.3	0.67	1.77	0.8	0.25	0.004	0.008		
SAE 4340		4										
BS 970 817 M40 (EN 24)		5	0.37	0.28	0.58	1.50	1.01	0.21	0.012	0.012	0.01	Cu 0.13
			0.4	0.2	0.6	1.6	1.1	0.3				
			0.42	0.25	0.59	1.38	1.01	0.29	0.03	0.016		Cu 0.16
			0.36	0.1	0.45	1.3	1.0	0.2				
			0.44	0.35	0.7	1.7	1.4	0.35				
			0.48	0.24	0.97	1.42	1.03	0.26	0.052	0.023		
			0.39	0.14	0.43	1.35	1.03	0.26	0.003	0.002		Cu 0.014
			0.42	0.25	0.59	1.32	1.01	0.29	0.025	0.016		Cu 0.16
			0.42	0.25	0.59	1.38	1.01	0.29	0.03	0.016		
			0.45	0.15	0.5	1.52	1.07	0.25	0.003	0.001		
			0.37	0.22	0.54	1.77	1.07	0.24	0.04	0.03		
BS 970 835 M30 (EN 30A)		6	0.35	0.14	0.44	4.23	1.43	0.13				
BS 970 835 M30 (EN 30B)		7	0.3	0.22	0.5	4.2	1.25	0.3				
1% Carbon steel		8	1.0	0.25	1.35		0.5	<0.035	<0.035	0.2		
AMS 6431 D6 AC		9	0.45	0.15	0.16	0.4	0.9	0.9	0.015	0.015	0.08	
			0.5	0.3	0.9	0.7	1.2	1.1	0.015	0.015	0.15	
			0.48	0.28	0.83	0.58	1.06	1.01	0.005	0.01	0.1	Cu 0.15
3Cr-Mo		10	0.33	0.32	0.80	0.18	3.10	0.57	0.02	0.02		Sn 0.013
Cr-Mo-V		11	0.32	0.3	0.89	<0.1	1.1	1.18	0.014	0.012	0.27	
3Cr-Mo-V		12	0.37	0.28	0.63	0.08	2.94	0.61	0.01	0.01	0.33	Nb ≤ 0.05
Fe-Cr-C		13	0.35				4.0					
Ni-Cr-(SNC 3)		14	0.36	0.25	0.41	3.1	0.77	0.07	0.006	0.02		Cu 0.16
3Ni-Cr-Mo-V		15	0.24	0.04	0.28	3.51	1.64	0.39	0.012	0.005	0.11	
			0.3	0.26	0.44	2.76	1.36	0.59	0.016	0.008	0.1	
			0.36	0.18	0.51	3.13	1.16	0.52	0.006	0.009	0.13	
			0.11	0.30	0.87	4.85	0.58	0.48	0.005	0.002	0.07	Al 0.01
5Ni-Cr-Mo-V		16	0.38	0.30	0.80	1.30	1.50	0.2				
34Cr-Ni-Mo6		17	0.35									
35 NCD 16		18										
HY-TUF		19	0.23	1.3	1.2	1.65	0.2	0.35				
HY-80		20	0.28	1.7	1.5	1.5	0.4	0.45	0.04	0.04		
			0.16	0.22	0.29	2.25	1.42	0.29	0.017	0.01		
			0.18	0.2	0.3	2.99	1.68	0.41	0.013	0.108		
			0.11	0.23	0.85	4.91	0.58	0.58	0.007	0.009	0.05	Al 0.021
HY-130		21	0.12	0.35	0.79	4.96	0.57	0.41	0.005	0.004	0.057	Al 0.059
			0.1	0.23	0.35	5.33	0.49	0.57	0.006	0.007	0.064	
(1)												
SCNM 439		22	0.36	0.32	0.76	1.81	0.82	0.17	0.016	0.017		Cu 0.06
			0.38	0.27	0.76	1.93	0.95	0.25	0.008	0.022		Cu 0.005

Note

- (1) The nickel content of this steel is greater than the 5 per cent maximum necessary for a steel to be classified here as low alloy, but it is included to complement the other HY-130 data.

DATA TABLE FOR FIGURE 1

Material designation form and thickness mm (in)	Notes	Derivation No.	f_t		f_p		R	Crack Growth Rate Taken from Figure				
								Range of da/dN		n	C	
			$\frac{MN}{m^2}$	$\frac{10^3 \text{ lbf}}{\text{in}^2}$	$\frac{MN}{m^2}$	$\frac{10^3 \text{ lbf}}{\text{in}^2}$		$\frac{m}{\text{cycle}}$	$\frac{\text{in}}{\text{cycle}}$		$m\left(\frac{m^{3/2}}{MN}\right)^n$	$\text{in}\left(\frac{\text{in}^{3/2}}{10^3 \text{ lbf}}\right)^n$
AISI 4140 Plate 3.5 (0.14)	1	32			883	128	0.05	2×10^{-9} to 6×10^{-9}	8×10^{-8} to 2.4×10^{-7}	2.2	3.9×10^{-11}	1.7×10^{-9}

HEAT TREATMENT NOTES

- (1) Austenitised at 1000°C for 1 hour, oil quenched, tempered at 650°C for 1 hour.

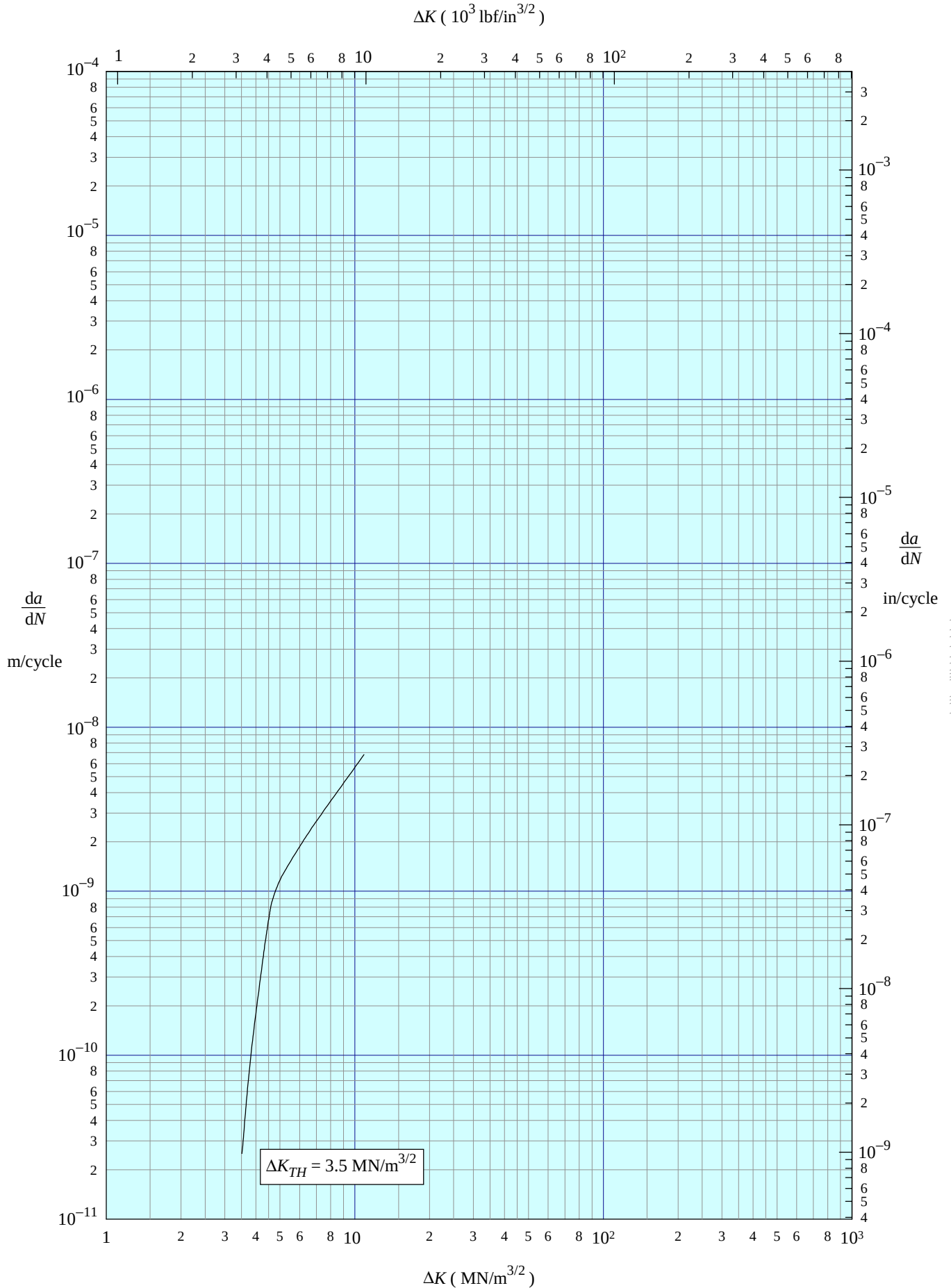


FIGURE 1 AISI 4140 ($R = 0.05$)

DATA TABLE FOR FIGURE 2

Material designation form and thickness mm (in)	Notes	Derivation No.	f_t		f_p		R	Crack Growth Rate Taken from Figure				
								Range of da/dN		n	C	
			$\frac{\text{MN}}{\text{m}^2}$	$\frac{10^3 \text{ lbf}}{\text{in}^2}$	$\frac{\text{MN}}{\text{m}^2}$	$\frac{10^3 \text{ lbf}}{\text{in}^2}$		$\frac{\text{m}}{\text{cycle}}$	$\frac{\text{in}}{\text{cycle}}$		$\text{m}\left(\frac{\text{m}^{3/2}}{\text{MN}}\right)^n$	$\text{in}\left(\frac{\text{in}^{3/2}}{10^3 \text{ lbf}}\right)^n$
AISI 4330 Plate 10.3 (0.407)		1	1240 to 1655	180 to 240	1120 to 1365	166* to 198*	0.05	2×10^{-7} to 9×10^{-7}	8×10^{-6} to 3.6×10^{-5}	1.7	5.7×10^{-10}	2.5×10^{-8}

* Mechanical properties from standard specifications.

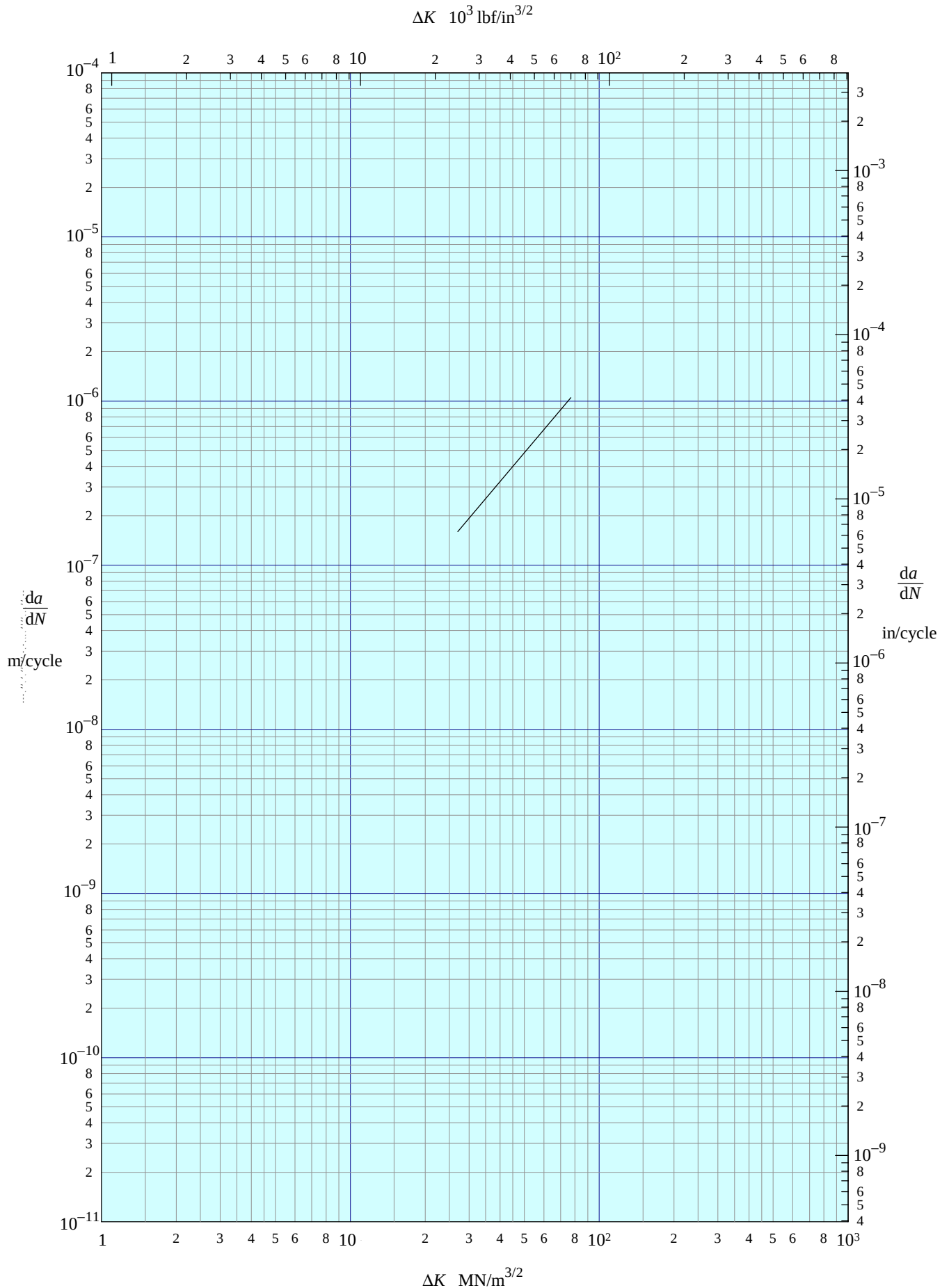


FIGURE 2 AISI 4330 ($R = 0.05$)

DATA TABLE FOR FIGURE 3

Material designation form and thickness mm (in)	Notes	Derivation No.	f_t		f_p		R	Crack Growth Rate Taken from Figure					
			$\frac{\text{MN}}{\text{m}^2}$	$\frac{10^3 \text{ lbf}}{\text{in}^2}$	$\frac{\text{MN}}{\text{m}^2}$	$\frac{10^3 \text{ lbf}}{\text{in}^2}$		Range of da/dN		n	C		
								$\frac{\text{m}}{\text{cycle}}$	$\frac{\text{in}}{\text{cycle}}$		$\text{m}\left(\frac{\text{m}^{3/2}}{\text{MN}}\right)^n$	$\text{in}\left(\frac{\text{in}^{3/2}}{10^3 \text{ lbf}}\right)^n$	
AISI 4340 (300M) 25 (1)		17	985 1337 199	143 194 2891	896 1240 1516	130 180 220	0.11						
12.7 (0.5)	1	26	1186	172	1074	156	0.05	7×10^{-9} to 2×10^{-8}	2.8×10^{-7} to 8×10^{-7}	3.4	1.3×10^{-12}	5.6×10^{-11}	
								2×10^{-8} to 6×10^{-7}	8×10^{-7} to 2.4×10^{-5}	2.9	5.4×10^{-12}	2.3×10^{-10}	
								6×10^{-7} to 2×10^{-6}	2.4×10^{-5} to 8×10^{-4}	3.1	2.6×10^{-12}	1.1×10^{-10}	
							0.7	2×10^{-9} to 2×10^{-8}	8×10^{-8} to 8×10^{-7}	2.8	2×10^{-11}	8.7×10^{-10}	
								2×10^{-8} to 2×10^{-7}	8×10^{-7} to 2.4×10^{-6}	2.7	2.5×10^{-11}	1.1×10^{-9}	
								2×10^{-7} to 6×10^{-7}	8×10^{-6} to 2.4×10^{-5}	2.5	4.4×10^{-11}	1.9×10^{-9}	
	2		1683	244	1497	217	0.05	1×10^{-9} to 7×10^{-9}	4×10^{-8} to 2.8×10^{-7}	5.0	9.5×10^{-14}	4.1×10^{-12}	
								7×10^{-9} to 2×10^{-8}	2.8×10^{-7} to 8×10^{-7}	3.2	4.8×10^{-12}	2.1×10^{-10}	
								2×10^{-8} to 6×10^{-7}	8×10^{-7} to 2.4×10^{-5}	2.6	2.2×10^{-11}	9.5×10^{-10}	
	3		2338	340	2107	306	0.05	3×10^{-9} to 2×10^{-8}	1.2×10^{-7} to 8×10^{-7}	2.7	4.4×10^{-11}	1.9×10^{-9}	
								2×10^{-8} to 2×10^{-7}	8×10^{-7} to 8×10^{-6}	3.6	5.4×10^{-12}	2.3×10^{-10}	
							0.7	2×10^{-7} to 6×10^{-7}	8×10^{-6} to 2.4×10^{-5}	4.3	5.6×10^{-13}	2.4×10^{-11}	
								2×10^{-9} to 7×10^{-9}	8×10^{-8} to 2.8×10^{-7}	3.2	3.4×10^{-11}	1.5×10^{-9}	
	4	35		1355	197	1269	184	0.1					
								0.5					
								0.1					
0.5													

HEAT TREATMENT NOTES

- (1) Austenitised at 870°C, oil quenched, tempered at 650°C for 1 hour.
- (2) Austenitised at 870°C, oil quenched, tempered at 470°C for 1 hour.
- (3) Austenitised at 870°C, oil quenched, tempered at 100°C for 1 hour.
- (4) Austenitised at 870°C for 1 hour, oil quenched, tempered at 510°C for 1 hour, air cooled.
- (5) Austenitised at 830°C for 1 hour, oil quenched, tempered at 565°C for 1 hour, air cooled.

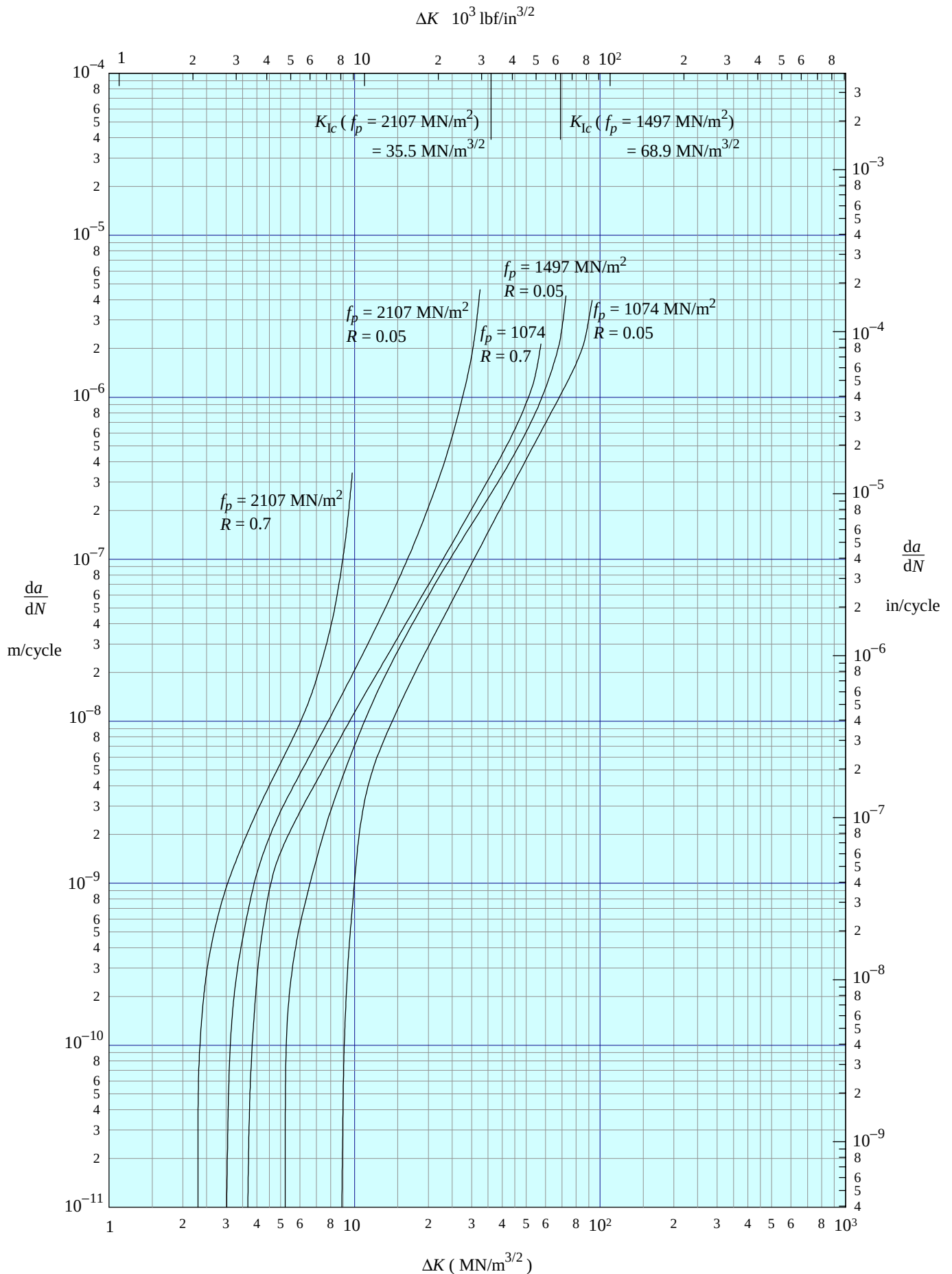


FIGURE 3 AISI 4340 (300M)