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S-N CURVE CONSTRUCTION FOR ALUMINIUM FORGING ALLOYS

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SUMMARY

An extensive programme of notched fatigue testing of aluminium forging alloys has shown that the data result in two basic forms of S-N curve. Analytical approaches to constructing the S-N curves were less satisfactory than fitting the curves freehand. Since freehand curve fitting must involve an element of subjectivity, guidelines for minimising this subjectivity have been proposed.

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INTRODUCTION

The NLR is presently conducting a long-term investigation of the notched fatigue properties of aluminium forging alloys in order to provide data for handbook presentation. The alloys are all of the high strength AlZnMgCu type (7000 series), and in the first instance only constant amplitude fatigue loading is considered.

It is customary to present constant amplitude fatigue test results in terms of the stress amplitude, Sa, plotted against the logarithm of the fatigue life, N, and to construct so-called S-N curves to fit the data. An often used method for constructing an S-N curve is to judge by eye the optimum position for a smooth curve passing through the data points and to draw the curve freehand. This method is obviously subjective and may be questioned whenever there is significant scatter in the data and when the fatigue limit is approached. Near the fatigue limit there will inevitably be both broken and unbroken specimens, widely apart in terms of fatigue life.

The risk of undue subjectivity would be removed if it were possible to obtain an analytical relation for the S-N curve. This possibility has been investigated recently by Harris (Ref. 1), who reviewed and compared several equations and methods for fitting S-N curves to test data, mostly for steels. In the present work the usefulness of these techniques for high strength aluminium forging alloys is checked. Guidelines are proposed for establishing the S-N curves.

ANALYTICAL APPROACHES TO S-N CURVE CONSTRUCTION

In reviewing the literature Harris (Ref. 1) reported three basic equations for analytically deriving S-N curves. These equations are:

$$S_a = S_\ell + \frac{\alpha}{N^\gamma} \tag{1}$$

$$\frac{S_a - S_\ell}{S_u - S_\ell} = e^{-k\,(\log N)^m} \tag{2}$$

$$\frac{S_u - S_a}{S_u - S_\ell} = \frac{2}{\pi} \text{ arc tan } \left(\frac{N^h}{\lambda}\right) \tag{3}$$

where S_a is the stress amplitude; S_ℓ is the fatigue limit; N is the fatigue life; α, γ, k, m, h and λ are material constants; and S_u is given by

$$S_u = \frac{S_a}{S_{max}} \text{ (UTS)} \tag{4}$$

where S_{max} is the maximum stress in the fatigue cycle and UTS is the ultimate tensile strength of the material.

Equations (1) - (3) can be linearized to the following forms:

$$\log\left(\frac{S_a - S_\ell}{S_\ell}\right) = \log\left(\frac{\alpha}{S_\ell}\right) - \gamma \log N \tag{1a}$$

$$\log\left(\ln\left[\frac{S_a - S_\ell}{S_u - S_\ell}\right]\right) = m \log (\log N) + \log (-k) \tag{2a}$$

$$\log\left(\tan \frac{\pi}{2}\left[\frac{S_u - S_a}{S_u - S_\ell}\right]\right) = h \log N - \log \lambda \tag{3a}$$

Provided that the fatigue limit, S_ℓ, has already been determined, these linear forms may be used to carry out a least squares analysis of the fatigue data and hence obtain values for the material constants in order to construct the S-N curve. Harris stated that S_ℓ could be found by plotting log S_a versus log N and conducting a linear regression analysis, or else from a curve drawn by eye through the test data. He found that the latter (subjective) estimate of S_ℓ gave the best results. As regards the choice of equation for constructing S-N curves, equation (2) gave slightly better fits to the data than equation (3), and both equations were significantly better than equation (1).

NLR DATA BASE FOR ALUMINIUM FORGING ALLOYS

An overview of the NLR long-term investigation is given in table 1. The total number of specimens involved is about 600, with generally 18 specimens available for establishing each S-N curve. This is a moderate number of specimens per S-N curve, hence the importance of considering different approaches in order to optimise S-N curve construction.

TABLE 1

OVERVIEW OF ALUMINIUM FORGING ALLOY NOTCHED FATIGUE TEST PROGRAMME

MATERIALS	:	7075-T73, 7175-T736, 7075-T736 die forgings
SPECIMENS	:	5 mm thick flat rectangular; elastic stress concentration factors (K_t) 2.1 and 3.1; K_t = 2.1 notches chromic acid anodised; axial loading in L (longitudinal), LT (long transverse) and ST (short transverse) directions
S-N CURVES	:	from 10^4 to 10^7 cycles at two constant minimum stress levels
TEST CONDITIONS	:	100 kN AMSLER VIBROPHORE operating at 115 Hz in laboratory air

At the time of preparation of this article approximately half the test programme had been completed. The results showed that there were basic differences in the form of the S-N curves. Some data sets enabled smooth, gradually sloping S-N curves to be drawn, while other data indicated a fairly abrupt "knee" between 10^5 and 5 x 10^5 cycles. Examples of each type are given in figures 1 and 2 with freehand curves fitted to the data. Gradually sloping S-N curves were favoured by testing in the ST direction and at high minimum stress values. S-N curves with "knees" were favoured by testing in the L direction and at low minimum stress values.

S-N CURVE ANALYSIS FOR ALUMINIUM FORGING ALLOYS

In view of Harris' results (Ref. 1) it was decided to analyse the two types of aluminium forging alloy S-N curves using equations (2) and (2a), and (3) and (3a). The analyses consisted of the following steps:

(a) A check whether data points for stress levels at which one or more specimens remained unbroken should be included for determining the material constants.

(b) Determination of the fatigue limits, S_ℓ.

(c) Least square analyses to find material constants k, m, h and λ.

(d) Construction of optimal S-N curves.

To check whether data points for stress levels at which one or more specimens remained unbroken should be included for determining material constants an estimate of S_ℓ from the freehand curve of figure 2 was made, and least squares analyses with and without inclusion of data for unbroken specimens were carried out using equation (2a) to determine k and m. It turned out that the data for unbroken specimens had a strong influence on the values of k and m and resulted in poor fitting of an S-N curve to the data at shorter lives. Thus all further analyses for determining material constants were conducted without including data for stress levels at which one or more specimens remained unbroken.

To determine S_ℓ neither of the approaches mentioned by Harris, i.e. linear regression analysis of a straightforward log S_a versus log N plot or a subjective estimate, were followed. Instead a number of values for S_ℓ were inserted into equations (2a) and (3a); the material constants k, m, h and λ were found; and a goodness-of-fit parameter was calculated according to

$$\omega^2 = \frac{\sum_{i=1}^{n} \left(S_{a_{i_{TEST}}} - S_{a_{i_{CALCULATED}}} \right)^2}{\nu} \qquad (4)$$

where ν is the number of degrees of freedom (= number of data points minus number of parameters). It is important to note that in the calculation of this parameter the data for stress levels at which one or more specimens remained unbroken were included, since at this stage in the analyses these only locally (but essentially) influence the fit of the S-N curves.

Figures 3 and 4 show the results of goodness-of-fit parameter calculations using the data in figures 1 and 2, and figures 5 and 6 give optimal S-N curves derived by using the goodness-of-fit parameter minimum values of S_ℓ to find k, m, h and λ.

Figures 3 and 5 show that equations (2) and (3) both give good gradually sloping S-N curve fits to the data shown in figure 1. Equation (3) gives a marginally better fit for lives between 10^4 and 10^5 cycles and at lives approaching 10^7 cycles. However, the differences between the analytical curves and also the freehand curve are small.

The fit of equations (2) and (3) to data with a "knee" is much less satisfactory. Figure 4 shows that the goodness-of-fit parameter minima are about eight times larger than in figure 3, and figure 6 reveals significant differences in the S-N curves. In particular the fit of equation (3) is poor.

It would appear that use of equation (3) should be preferred for fitting a smooth gradually sloping S-N curve, while equation (2) is preferable for data with a "knee". The fact remains, however, that neither equation adequately accounts for the distinct differences between the sets of test data. This being so, it is our opinion that the current best method for fitting S-N curves to the data from the total test programme is to draw the curves freehand.

At first impression a recommendation to construct S-N curves freehand might seem a retrograde step. However, unavoidable subjectivity can be limited by following a number of guidelines, as will now be discussed.

GUIDELINES FOR FREEHAND CONSTRUCTION OF S-N CURVES

The choice of guidelines for freehand construction of S-N curves is of itself somewhat subjective. Two generally used guidelines are:

(1) At stress levels for which all specimens fail before 10^7 cycles the S-N curve is based on the logarithmic mean life.

(2) The fatigue limit must always be higher than a stress level at which all specimens remain unbroken.

In addition, for the NLR aluminium forging alloy notched fatigue test programme the following conditions have been instituted as guidelines:

(3) The fatigue limit is taken to be the nearest integral value of S_a in MPa at 10^7 cycles.

(4) At stress levels for which specimens exhibit lives longer and shorter than 10^7 cycles the fatigue limit is lower and is determined by the ratio of failed to total number of specimens and the differences between stress levels. For example, if the difference between two adjacent stress levels is 5 MPa and three out of five specimens have failed before 10^7 cycles at the higher stress level but none have failed before 10^7 cycles at the lower stress level, then the fatigue limit is 3 MPa lower than the higher stress level.

The foregoing guidelines must not significantly disturb the smooth passage of the S-N curve through the data points. Thus, the determination of the fatigue limit with the help of guidelines (3) and (4) must also take into account the logarithmic mean life at the next highest stress level and the steepness of the S-N curve in the finite life regime. These two latter considerations are not, however, allowed to alter the fatigue limit by more than ± 2 MPa.

The balancing of guidelines (3) and (4) against the requirement of a smooth passage of the S-N curve through the data points can be clarified by two brief examples:

(a) According to the guidelines the fatigue limit in figure 1 would be 26 MPa. However, this value would not enable a smooth curve to be drawn through the data for $S_a = \pm 30$ MPa, since these tests gave relatively long lives (1.5×10^6 to $> 10^7$ cycles). The fatigue limit has therefore been established at 28 MPa.

(b) According to the guidelines the fatigue limit in figure 2 would be 44 MPa. The data clearly indicate that the S-N curve should have a "knee" rather than a gradual shape, and so there appears to be no reason for altering the fatigue limit from that given by the guidelines.

SUMMARY

An extensive programme of notched fatigue testing of aluminium forging alloys has shown that the data result in two basic forms of

S-N curve. Analytical approaches to constructing the S-N curves were less satisfactory than fitting the curves freehand. Since freehand curve fitting must involve an element of subjectivity, guidelines for minimising this subjectivity have been proposed.

REFERENCE

1. W.D. Harris, "A search for a consistent method of S-N curve construction with limited data", Paper 79-47, 35th Annual National Forum of the American Helicopter Society, Washington, D.C., May 1979.

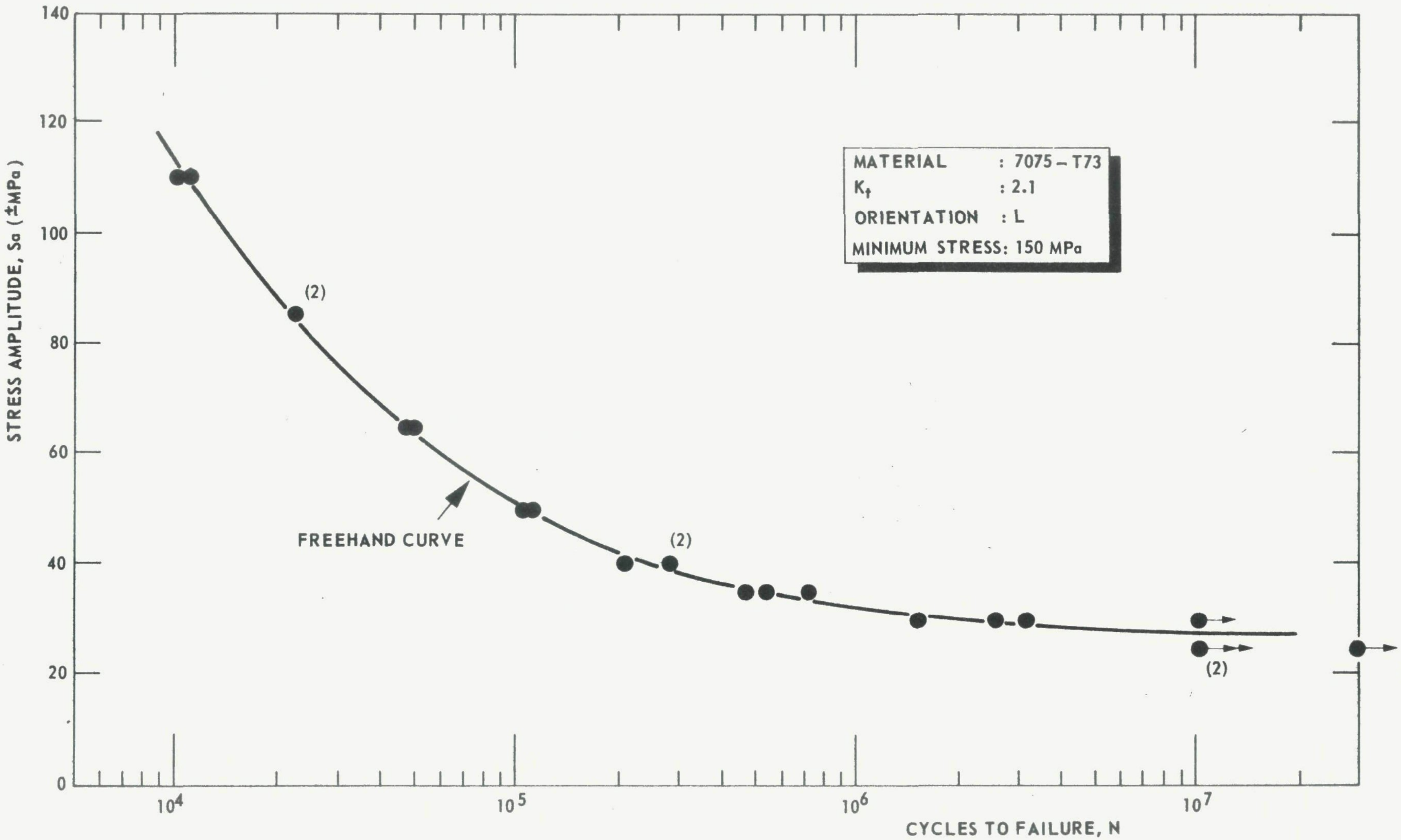

Fig. 1 Example of a smooth, gradually sloping S-N curve

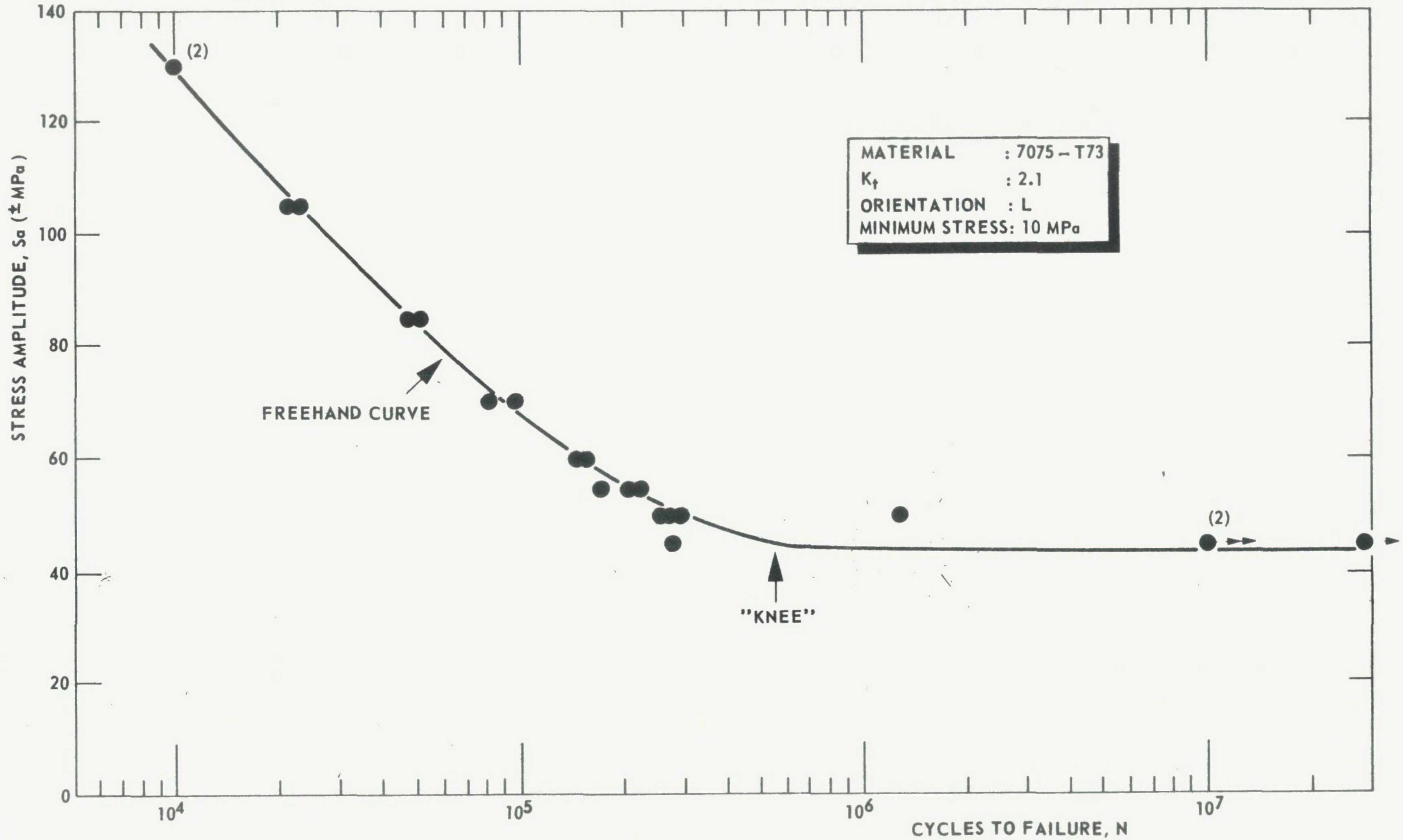

Fig. 2 Example of an S-N curve with a "knee"

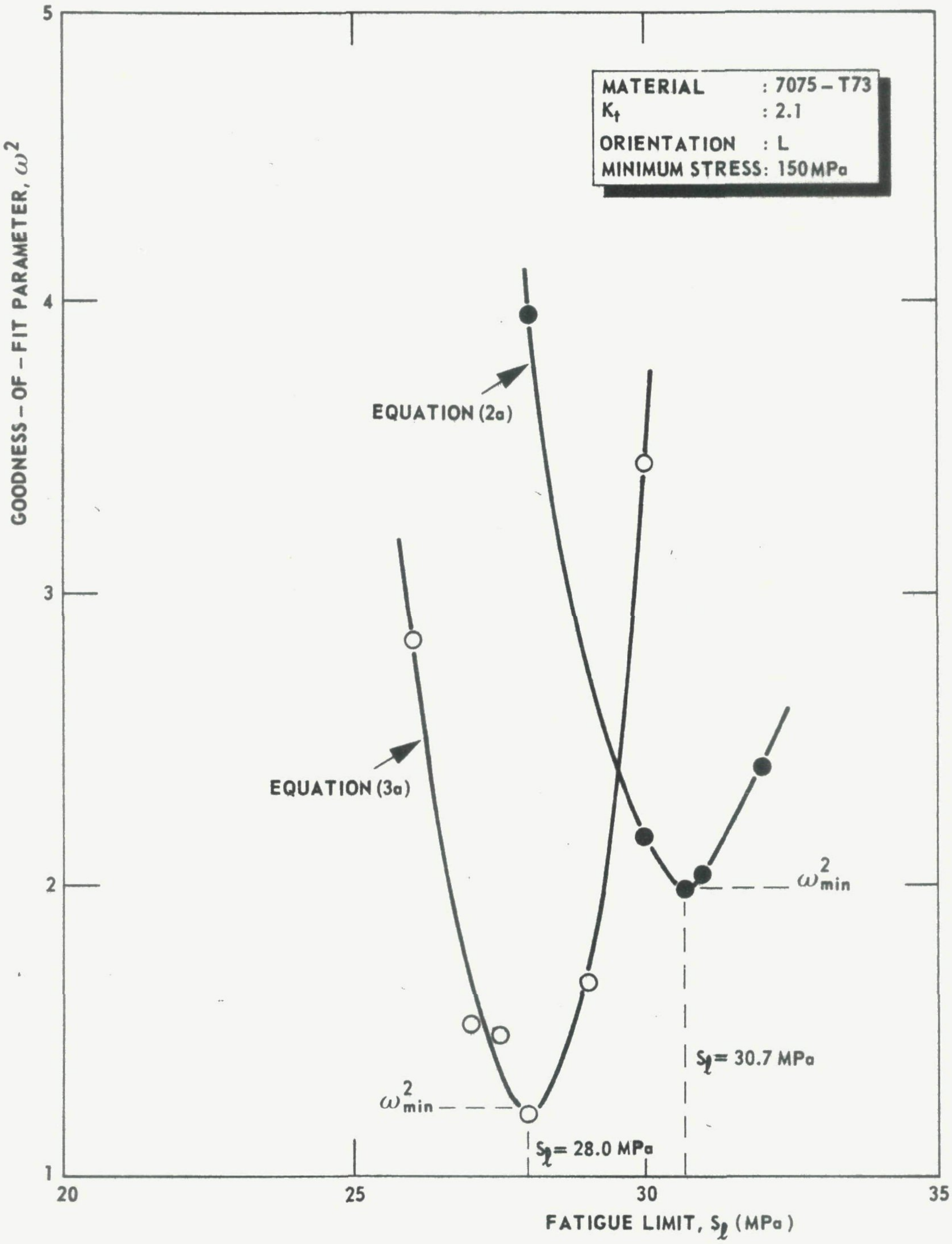

Fig. 3 Determination of S_ℓ for constructing an optimal analytical S-N curve to fit the data in figure 1

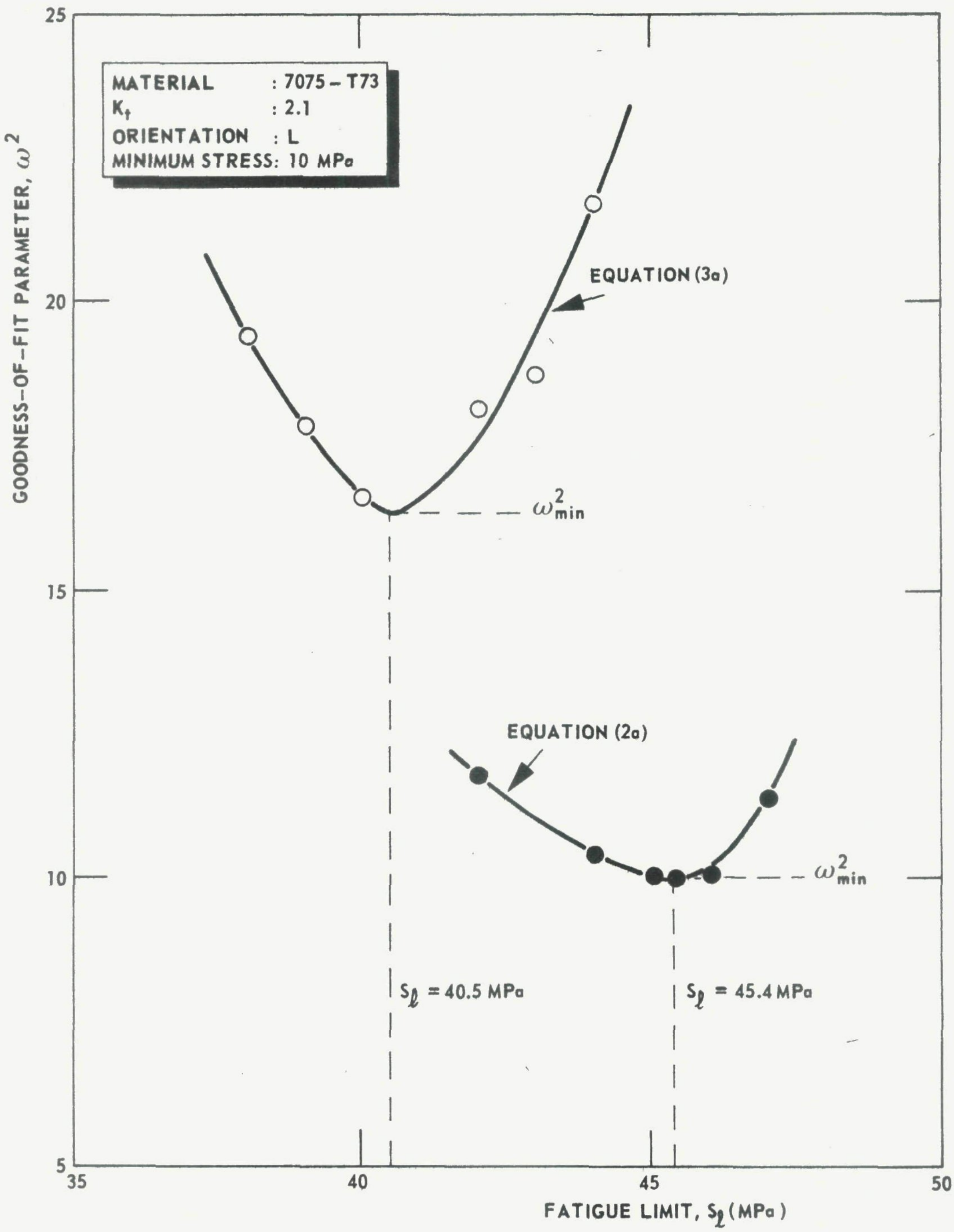

Fig. 4 Determination of S_ℓ for constructing an optimal analytical S-N curve to fit the data in figure 2

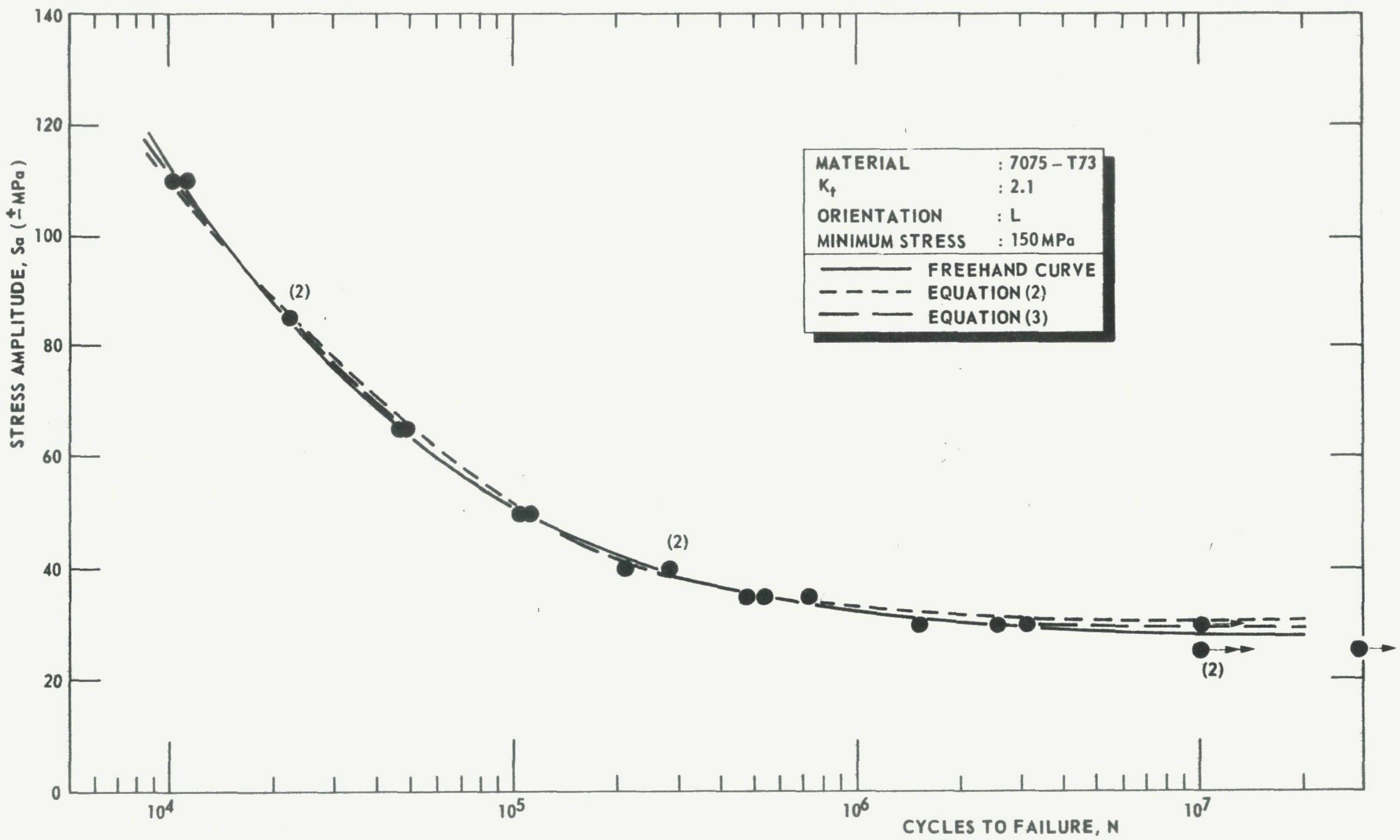

Fig. 5 Optimal S-N curves for fitting to the data of figure 1

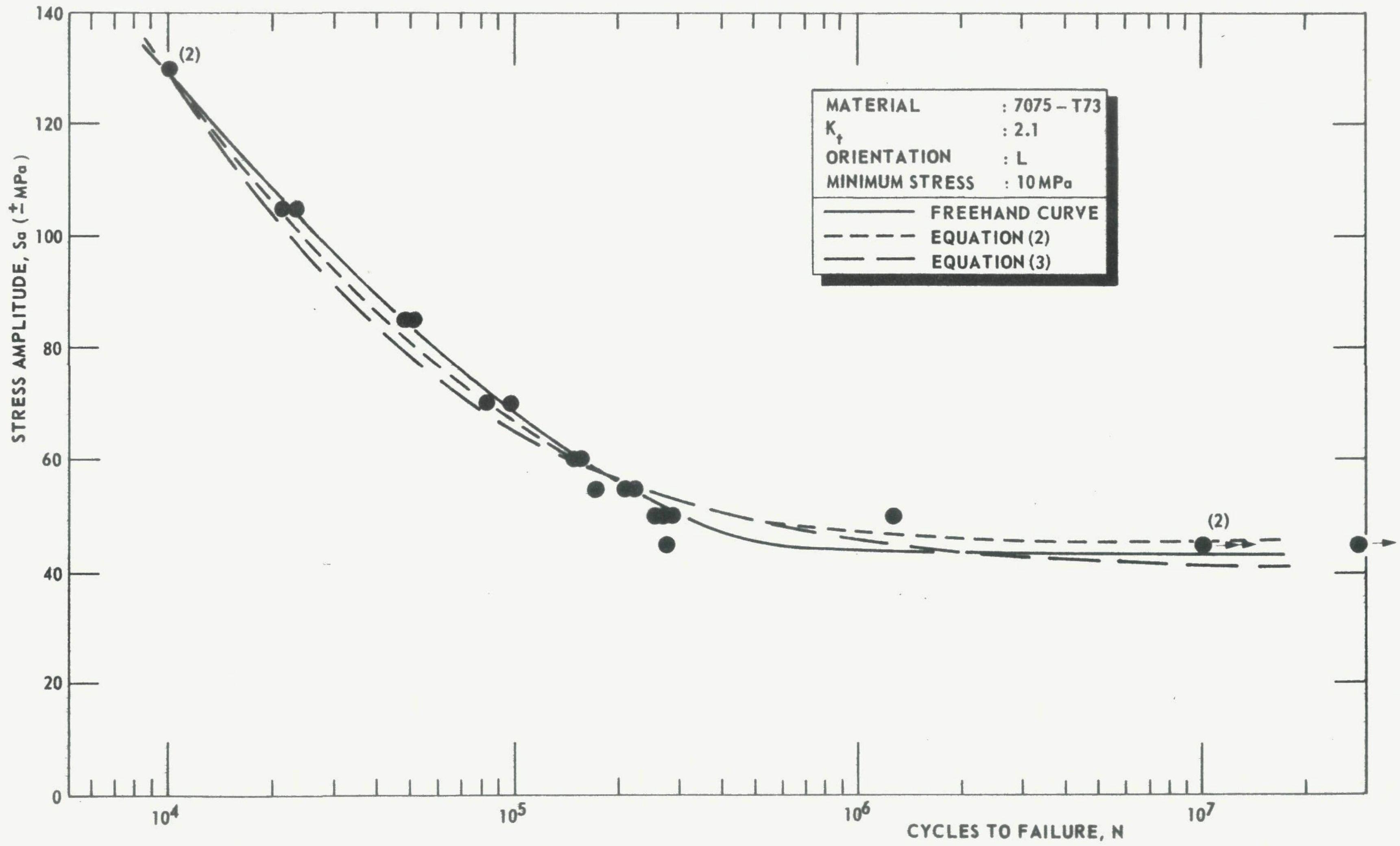

Fig. 6 Optimal S-N curves for fitting to the data of figure 2