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A Comparative Study of the Fatigue Performance of Notched Specimens of Clad and Unclad Aluminium Alloy, with and without a Pre-Stress

by

P. R. Edwards and M. G. Earl

Structures Dept., R.A.E., Farnborough

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A COMPARATIVE STUDY OF THE FATIGUE PERFORMANCE OF NOTCHED SPECIMENS OF CLAD AND UNCLAD ALUMINIUM ALLOY, WITH AND WITHOUT A PRE-STRESS

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SUMMARY

The sensitivity of 2L71 (unclad) and 2L73 (clad) aluminium alloy to residual stresses was determined by measuring the improvement in the constant amplitude fatigue strength of notched specimens due to the application of a single large tensile stress at the start of the test. It was found that the clad specimens were markedly less affected by the pre-stress than the unclad. This lack of response in the clad specimens was attributed to the low yield point of the cladding which reduced the susceptibility of this material to residual stresses.

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* Replaces RAE Technical Report 75148 - ARC 36725

CONTENTS

1 INTRODUCTION

Aluminium alloy in the clad form is commonly in use in the aircraft industry where it is desired to have good resistance to corrosion. It is well-known that the fatigue performance of clad material under normal laboratory testing conditions is inferior to that of the bare material in both notched[1] and plain[1,2] configuration under constant amplitude loading. However there is only limited information on the relative fatigue strengths of the two materials under variable amplitude loading and therefore differences in cumulative damage behaviour between clad and unclad aluminium alloys are not well understood. By cumulative damage behaviour is meant here the general relationship between fatigue lives under constant and variable amplitude loading and the performance of Miner's rule in particular (see Appendix A).

Available information suggests that Miner's rule does, in fact, give values of $\sum \frac{n}{N}$ which differ significantly between the two types of material for one particular type of test. In a previous investigation[3], a literature survey was made in which the performance of Miner's rule was assessed in predicting fatigue life of plain and notched specimens at zero mean stress under simple low-high and high-low step loading. These tests were basically constant amplitude loading with one change in stress level at some predetermined point in the fatigue life. It was found that for unclad material, low-high tests gave $\sum \frac{n}{N}$ greater than unity and high-low tests gave $\sum \frac{n}{N}$ less than unity; for clad material these results were reversed. Although the step test is not representative of service loading conditions, the above differences in behaviour between clad and unclad material raise the possibility of other differences on cumulative damage behaviour which could be significant in practical cases. Accordingly, a programme of research was started in order to study differences in cumulative damage behaviour between clad (2L73) and unclad (2L71) notched ($K_t = 2.3$) aluminium alloy specimens. This Report is the first to be issued on this programme, and covers constant amplitude tests with and without a pre-stress.

Section 2 of this Report summarises factors which can affect the accuracy of Miner's rule. It is then shown in section 3 that differences in cumulative damage behaviour could arise from differences in sensitivity to at least one of these factors, the effect of residual stresses; such stresses generated at points of fatigue initiation by high loads in a variable amplitude loading sequence can strongly affect cumulative damage behaviour[3]. Recently a cumulative damage rule to account for this effect has been published by the Engineering Sciences Data Unit[4]. It is shown in this data sheet that for a number of cases there is an improvement over Miner's rule when using the new rule to predict the fatigue life of unclad notched specimens of aluminium alloy. The application of the ESDU rule to clad specimens has not been similarly evaluated. However in section 3 of this Report it is shown by consideration of the calculated stress states at the notch root under fatigue loading that the fatigue lives of specimens in clad material are not likely to be affected by residual stresses to the same extent as those in the bare material.

The experimental work described in section 4 covers the first phase of the research programme. It consists of, first, tests to compare the performance of specimens in the two materials under constant amplitude loading at a tensile mean stress, and second, tests to determine the sensitivity of the two types of specimen to residual stresses. This second comparison was achieved by subjecting each specimen to a tensile pre-stress before fatigue testing in order to introduce a compressive residual stress at the notch root. Constant amplitude fatigue loading was then applied at a tensile mean stress, and any improvement in fatigue strength due to pre-stressing was taken as resulting from the residual stresses.

As described in the discussion of section 5, increases in fatigue strength of up to 47 per cent due to pre-stressing were found on the unclad specimens, but the corresponding percentage increases in fatigue strength on the clad specimens were generally less than one half of this. It was therefore concluded that if the ESDU method were applied to clad specimens without taking account of the cladding, the accuracy of the method would differ from that on unclad specimens.

Further work, described in section 6, is planned using random loading. The results of this work should shed further light on differences in cumulative damage behaviour between the two forms of material, and quantify those differences for loading more representative of service conditions.

2 FACTORS WHICH CAN AFFECT CUMULATIVE DAMAGE

In a previous investigation[3] which was subsequently updated[5] a review was made of factors which can affect cumulative damage behaviour, i.e. cause Miner's rule to give values of $\sum \frac{n}{N}$ other than unity. Of the factors considered the following were regarded as being significant.

(1) Residual stresses arising from stress redistribution around the point of fatigue initiation under high loads in the loading sequence. Residual stresses are predominantly compressive (beneficial) for notched aluminium alloy specimens under symmetrical spectrum loading at a tensile mean stress, and tend to increase $\sum \frac{n}{N}$.

(2) Cycles below the initial fatigue limit which do no damage according to Miner's rule but which in practice can increase or decrease $\sum \frac{n}{N}$.

(3) The variation of relative damage rate with stress. This can increase or decrease $\sum \frac{n}{N}$ in step tests, i.e. constant amplitude loading in which there is only one change in stress amplitude during the fatigue life. Also it can reduce $\sum \frac{n}{N}$ in spectrum fatigue tests. This effect has been termed 'stress dependence' by Kaechele[6]. In Ref.3 it was suggested that this effect was not likely to be large for spectrum loading conditions. However a reappraisal was made in Ref.5 and it was concluded that this could be a significant factor in giving typical $\sum \frac{n}{N}$ values of 0.3 for plain and notched specimens of steel and aluminium alloy at zero mean stress under Gaussian random loading.

(4) Stress dependent interaction. This name is given to a class of process which can affect $\sum \frac{n}{N}$. The relevant feature is that fatigue damage rate at one level of alternating stress can be altered by previous cycling at a different level. The residual stress effect, although considered separately above, is in fact a member of this class. Another example is the well-known 'coaxing' effect in steels. There is, in addition, the possibility of other as yet undefined members of this class of process.

In this present programme to determine differences in cumulative damage behaviour between clad and unclad notched aluminium alloy specimens all these four factors will be considered. However, the work described in this first Report deals only with the effects of residual stresses on the two types of specimen under constant amplitude fatigue loading.

3 POSSIBLE EFFECTS OF RESIDUAL STRESSES ON CLAD MATERIAL

In a programme of work carried out by Hunter and Fricke[2], 24S-T3 plain specimens both clad and unclad were subjected to constant amplitude fatigue loading at zero mean stress. It was found that for the clad material, fatigue cracks initiated very early in the cladding, remained in the cladding for some time and subsequently progressed through to the core material. The result of the early initiation in the cladding was that the clad material showed inferior fatigue properties at the lower stress levels. It is reasonable to assume that the same mechanism was responsible for the inferior performance of clad material over unclad material in the notched configuration, found by Schijve and Jacobs[1]. It follows therefore that for notched and plain clad specimens, the early stages of the life are predominantly influenced by the cladding rather than by the core material.

In a review and programme of work on (unclad) lug specimens of aluminium alloy by Edwards[5] it was shown that residual stresses generated at stress concentrations by high loads in a variable amplitude loading sequence, and acting in the early stages of fatigue life, can affect the fatigue life under random and constant amplitude loading such that the accuracy of Miner's rule is affected. It will be demonstrated here that for clad specimens, the early part of the fatigue life, which is predominantly influenced by the cladding, is not likely to be affected greatly by such stresses under any loading action.

A well known effect of residual stresses is the extension of the fatigue life of a notched aluminium alloy specimen by the application of a high tensile load before starting fatigue testing. This can be illustrated by consideration of the local stresses at the notch root, first under constant amplitude loading and then under the action of a pre-stress followed by constant amplitude loading. Fig.1 represents the calculated behaviour of the material at the root of a notch of a specimen of L65 aluminium alloy (similar to 2L71) with a stress concentration factor of 2.3 and subjected to constant amplitude loading at a net mean stress of $125\mathrm{MN/m^2}$. For reasons which will become clear later the alternating stress was chosen to represent the fatigue limit stress of a clad specimen at the same mean stress (the stress versus strain data is taken from Ref.7). For a specimen not subjected to a pre-stress the material at the notch root behaves purely elastically, the local stress under constant amplitude loading varies between B and C, and the local mean stress is given by A. If, however, the specimen is subjected to a net pre-stress of $300\mathrm{MN/m^2}$, the material at the root of the notch is overstrained and behaves plastically up to point D. On unloading down to the net mean stress value the material behaves elastically down to E and application of the fatigue loading causes the material to cycle between F and G. At this point the local semi-range of alternating stress amplitude is given by EF, which is the same as AB, the local semi-range of alternating stress without a pre-stress. However, the local mean stress has now been lowered and is given by E, this lowered value being due to a residual stress which is the difference between the stress at A and the stress at E. This low local mean stress then reduces the rate of fatigue damage compared with that which would have been obtained before the pre-stress, and so increases the fatigue strength. In addition there will be a reduction in fatigue strength due to damage caused by the single half cycle of strain which induced the residual stress, but this will be very much smaller than the opposing increase and will not materially affect the following argument[5]. An estimate of the magnitude of increase in fatigue strength may be obtained by reference to plain specimen data. It has been shown[8] that the fatigue performance of a notched specimen during the early part of the fatigue life may be represented with reasonable accuracy by a plain specimen subjected to the same stress and strain history as the material at the root of the notch. Therefore, the increase, due to the residual stress, in fatigue strength during the early part of the life of the notched specimen will be similar to that between two batches of plain specimens of the same material, one batch tested at a mean stress given by point A on Fig.1 and the other at a mean stress given by point E. Reference to relevant data[9] on the effect of mean stress on plain specimens, predicts an increase in fatigue strength due to pre-stressing of approximately 55 per cent for the early part of the fatigue life of the specimen referred to in Fig.1.

In the case of specimens of clad material subjected to the same load history, i.e. as described above, the core material will behave in virtually the same fashion as before. (The local stresses will be slightly higher than before due to load shedding from the weak cladding, but this will be ignored here for simplicity.) The cladding at the root of the notch will be constrained to follow the same strain history as that of the adjacent core material. The predicted behaviour of the cladding is shown at the bottom of the diagram on Fig.1 and has been constructed from a stress versus strain curve of 99.8 per cent aluminium in the annealed condition[10]. It can be seen that because the cladding has a very low yield point, in tests without a pre-stress the material follows the line OHJH etc. giving maximum local stresses far below those in the core. In predicting the behaviour of the material between H and J it can be seen that an allowance has been made for the Bauschinger effect (the lowering of the magnitude of the tensile or compressive yield point after compressive or tensile yield respectively, which has resulted in a hysteresis loop). The local mean stress is given by point P. For the case of the pre-stress followed by constant amplitude loading the material will follow the line OKLML etc. The local mean stress is then given by point Q. Plain specimen data can now be used as above to predict the effect of pre-stressing on fatigue strength. This time, however, the plain specimen data required is for the cladding material, and the mean stresses before and after pre-stressing are given by P and Q on Fig.1. The difference in fatigue strength calculated then refers only to that part of the fatigue life during which time the fatigue process is confined to the cladding. The local mean stress values given by P and Q on Fig.1 are approximately +17 per cent and -7 per cent of the ultimate tensile strength. Reference to plain specimen data[11] for the cladding material indicates that the difference in fatigue strength due to change in local mean stress between these two values is likely to be only about 4 per cent. This compares with the figure of 55 per cent referred to above for the unclad material. Recalling that the alternating stress in Fig.1 was chosen to represent the fatigue limit of notched clad specimens at that mean stress, it is clear that any alternating stresses above this value would produce more plasticity which would in turn give rise to local mean stresses in the cladding closer to zero than those shown in Fig.1, for the cases both with and without a pre-stress. Therefore, local mean stresses set up by large unidirectional net stresses are unlikely to be large enough to have much effect on the alternating fatigue strength of the cladding for fatigue loading of any significant amplitude.

It follows then that whilst the fatigue process is confined to the cladding, residual stresses are unlikely to have much effect on cumulative damage behaviour. Therefore provided the fatigue process remains confined to the cladding for a significant proportion of the fatigue life, clad specimens are likely to be far less affected by residual stresses than unclad.

4 FATIGUE INVESTIGATION

In order to test the hypothesis of section 3 notched specimens of 2L71 (unclad) and 2L73 (clad) material were subjected to constant amplitude loading at a net mean stress of $125MN/m^2$ ($80MN/m^2$ gross), both with and without a pre-stress. Pre-stressing, which was carried out in order to induce a compressive residual stress at the notch root, consisted of loading each specimen to a net stress of $300MN/m^2$, and returning to the mean stress, before applying fatigue cycles at that mean stress.

A diagram of the specimens used, and the loading pins is given in Fig.2. Only light deburring on the central hole was permitted so as to avoid removing the cladding on the 2L73 specimens. Average curves of stress versus strain are given in Fig.3 for both materials and nominal chemical compositions are given in Table 1. Both materials showed proof and ultimate stress values greater than specification minima, and proof/ultimate ratios greater than specification. This is typical for these materials. For each material, all specimens were cut from a single sheet of 14 SWG (2.03mm) alloy measuring 6ft × 3ft (1.83m × 0.91m). (See Appendix B.)

Fatigue tests were carried out on a modified 20 ton short base Schenck resonant fatigue machine which has been described previously[12]. This machine can apply constant amplitude, Gaussian narrow band, or programmed random loading[3,5] at a frequency of approximately 112Hz. For the work described in this Report only constant amplitude loading was used.

The locations of the fatigue test results are given in the table below:

Locations of fatigue test results		
	2L71 (unclad)	2L73 (clad)
Constant amplitude without pre-stress	Table 2 Fig.4	Table 4 Fig.6
Constant amplitude with 300MN/m^2 pre-stress	Table 3 Fig.5	Table 5 Fig.7

Three of the tests on unclad specimens failed at the end lug rather than at the test section and are recorded on the appropriate S-N curves as unbroken. Up to the stage in the testing programme that the lug failures occurred, completely cylindrical loading pins were used. Subsequently, pins with machined flats were used at the lower stress levels after the manner described by Clarke[13], and this satisfactorily extended the fatigue life of the lugs. Cylindrical pins and pins with machined flats are shown in Fig.2. Cylindrical pins were still used at the higher stress levels since some distortion of the loading waveform occurred at these levels when pins with flats were used.

In plotting the S-N curves for 2L71 with and without pre-stress (Figs.4 and 5) the log means and standard deviations were first calculated and plotted. In cases where some specimens were unbroken (or if they failed at the lug) the log mean and standard deviation values were calculated by the method of Lariviere[14]. In this method the log mean and standard deviation are first calculated for the failed specimens. The log mean and standard deviation are then adjusted to apply to the whole population, using factors dependent only upon the ratio of number of failed to number of unfailed specimens. The basis of the method is the assumption that the ultimate lives of all the specimens, failed and unfailed, are distributed log normally. After plotting the log means and standard deviations, a smooth curve was drawn by eye, using the log means as a basis.

For the clad (2L73) specimens without pre-stress (Fig.6) after testing seven and eight specimens at 30 and $40 MN/m^2$ rms respectively it was decided that the scatter was lower for this material, so fewer specimens were tested per S-N curve. S-N curves for the clad material were drawn by eye. Scatter is discussed further in section 5.4.

All fracture surfaces were examined using an optical microscope in order to determine the number and positions of the fatigue origins. An origin was counted as significant if the crack propagating from the origin covered an area equal to or greater than a circle of 0.05mm diameter, equivalent to the full field of view on the microscope at ×300 magnification. Typical fatigue origins are shown in Fig.8. Origins were classified into two types, those originating from a corner as in Figs.8a and 8b, and those originating from a position along the bore as in Fig.8c.

The total numbers and types of significant origin on each specimen are given in Tables 2 to 5, together with the type of origin from which the largest crack started. In these tables, C represents a corner origin and B represents a bore origin.

5 DISCUSSION

5.1 Comparison of fatigue strengths of clad and unclad specimens under constant amplitude loading without pre-stress

Fig.9 compares the mean fatigue strengths of clad and unclad specimens without pre-stress and shows a markedly inferior performance for the clad material.

In seeking an explanation for this, it is instructive to consider the stress changes which will take place in the clad specimens due to the low tensile properties of the cladding. In this connection it should be noted that the basis of the comparison in Fig.9 is net stress including the cladding for the 2L73 specimens. Turning to Fig.1 it is clear from a comparison of the stress versus strain curves for the cladding and core that a substantial part of the mean stress, which from elastic theory would be expected to be carried by the cladding, will in fact be shed into the core by local yielding. Since the cladding is 10 per cent of the total thickness the core mean stress will be up to 10 per cent higher than in the unclad specimens. However, still referring to Fig.1, the alternating stress carried by the cladding is likely to be substantially that predicted from elastic theory at the fatigue limit. Therefore under these conditions the local mean stress in the cladding will be close to zero, which is beneficial relative to the unclad case, and the local mean stress in the core will be up to 10 per cent higher than for the unclad, which is deleterious. Provided the fatigue strength of the cladding is low enough to ensure that fatigue crack initiation always starts in the cladding, then the deleterious effect of the cladding is likely to be due to two factors. The first is the effect of the raised local mean stress in the core on the crack propagation rate, and the second is the low fatigue strength of the cladding. It has been shown[15] that fatigue crack propagation rate is generally less affected by mean stress than by alternating stress. Also the fatigue process may well be confined to the cladding for a substantial part of the life. Taking all the above factors into account the overall deleterious effect on fatigue strength of the raised core mean stress in the clad material is likely to be substantially less than 10 per cent at the fatigue limit.

As seen in Fig.9, the fatigue strength at 10^7 cycles for the clad specimens was approximately 30 per cent below that for the unclad. From the foregoing discussion it appears that this difference is due mainly to the poor fatigue performance of the cladding.

Fig.9 shows that on increasing the stress level the difference in fatigue properties progressively reduced, until at 10^5 cycles to failure the measured difference in fatigue strength was approximately 13 per cent.

The fact that cladding is more damaging at the lower stress levels may be explained as follows. It was noted by Hunter and Fricke[2] that on plain clad specimens the first crack detectable by a replica method could be observed at 1 per cent of the fatigue life and earlier. These cracks subsequently initiated fatigue cracks in the core after fewer cycles at the lower stress levels than were necessary to initiate cracks of the same total length in unclad specimens at the same stress level, thus giving shorter lives. Further, measurements on unclad specimens showed that crack initiation was completed at a much earlier percentage of fatigue life at high stresses than at low stresses (similar results have been reported by Schijve and Jacobs[16] and Manson[17]). Therefore any process, such as cladding, which speeds the initiation of fatigue cracks is likely to have less effect at high stresses than at low stresses.

5.2 Effect of pre-stressing on the clad and unclad specimens

Fig. 10 shows the S-N curves for the unclad specimens with and without pre-stressing, and Fig. 11 shows the same for the clad specimens. It is clear that the effect of pre-stressing was much greater on the unclad specimens than on the clad specimens. This is further demonstrated in Fig. 12 which shows the percentage increase in fatigue strength, plotted against life to failure, for the two types of specimen. For lives above 4×10^5 cycles the percentage increases in fatigue strength of the clad specimens due to pre-stressing were less than one half of those obtained on the unclad specimens.

This result is qualitatively consistent with the argument put forward in section 3. The smaller increase in fatigue life of the clad specimens due to pre-stressing is likely to be due to the fact that residual stresses were not very effective whilst the fatigue crack was confined to the cladding. However, the maximum increase due to pre-stressing in the fatigue strength of the clad material was as high as 20 per cent, as can be seen from Fig. 12, compared with the maximum value of 4 per cent expected from the argument of section 3 (assuming that the crack was confined to the cladding throughout the life). This difference is probably due to the influence of residual stresses in the core material when they would be likely to slow the cladding/core initiation, and also slow the crack propagation rate in the core. Even so, one of the most interesting aspects of these results is that the difference in response of the two forms of material was so large. That such a large effect resulted from the absence of residual stresses in the small (5 per cent) thickness per side of cladding, emphasises the importance of the early stages of life in determining the magnitude of residual stress effects on fatigue life.

The most important practical implication of these results is that it is important when interpreting the results of fatigue tests on aluminium alloy components to take account of whether or not the material is clad. Not only is the constant amplitude fatigue strength of notched and unnotched clad material different from unclad, but the cumulative damage behaviour may be different, particularly with regard to sensitivity to residual stresses. This should be borne in mind when applying the ESDU cumulative damage rule[4] which was mentioned in section 1. The difference in sensitivity of the two types of material to residual stresses implies that the accuracy of the rule may be different in the two cases. It should be noted, however, that the work described in this Report only applies to the case of fatigue initiation from a simple stress concentration. Similar behaviour will not necessarily be found in joint configurations where initiation may be from an area of fretting either between two sheets or between a rivet or bolt and the bore of a hole. Also the intensity of deburring or the presence of a chamfer at the test section is likely to determine whether or not a specimen will display the characteristics of clad specimens as described in this Report.

5.3 Fracture surface examination

As was described in detail in section 4, most of the fracture surfaces were classed as originating either from a corner or from along the bore of the hole. The total numbers and types of significant origins are given in Tables 2 to 5. On completion of fatigue testing some fracture surfaces were not available for examination and are labelled as such in the appropriate tables. Typical examples of fatigue origins are given in Fig.8.

In the following discussion more attention is paid to the mode of crack initiation (corner or bore) of the origin from which first failure occurred, rather than to the number or origins. The number of origins was not regarded as particularly significant because, especially at the lower stress levels, failure would commonly occur first at one side of the hole, with the crack propagating right across one side of the specimen. One result of this was to double the alternating and mean stress at the other side of the hole. This raised stress would then produce failure at the second side of the hole well within 10 per cent of the time to first failure (failure of the second side was the point at which the life was recorded). However, extra origins were liable to appear at the second side of the hole during the last period of the raised stresses.

The prime object in the examination of the fracture surfaces was to see whether or not all the clad specimens failed from fatigue cracks originating from the corners. If all the cracks originated from corners this would be consistent with the idea that cladding was the controlling factor in initiation. If, in addition, the unclad specimens failed from bore origins or a mixture of bore and corner origins, this would be further evidence for cladding having a strong effect on initiation. In fact, as can be seen from Tables 4 and 5, of the 36 clad specimens examined, only two contained cracks originating from the bore of the hole. One of these cracks on specimen H6S, Table 4, was the dominant crack, from which failure occurred, the other, on specimen H81S, Table 4, was a secondary crack. Both these specimens were tested at a high stress level where the scatter bands of the clad and unclad specimens overlapped. The occurrence of bore origins only at high stresses was taken as being consistent with section 5.1, which showed that cladding was likely to be much more important at the lower levels than at the higher levels.

The unclad specimens not subjected to a pre-stress also showed initiation predominantly from the corners, as can be seen from Table 2. Only two bore origins were found on the 27 specimens examined and these gave rise to only secondary cracks. For the pre-stressed unclad specimens, however, as can be seen from Table 3, cracks originating from the bore were the dominant cracks resulting in failure in five of the 21 specimens examined, and one secondary bore origin was found also. The reason for this increase in the number of bore origins is discussed further in section 5.5. The significance of this with regard to the effects of cladding, however, is that no bore origins whatsoever were found on the pre-stressed clad specimens, as can be seen from Table 5. For the pre-stressed specimens therefore, it can be deduced that the effect of cladding was to change the mode of failure from a mixture of bore and corner origins, to failure from corner origins alone.

It is concluded that the observations described in this section are consistent with cladding being the controlling factor in initiation in the clad specimens under constant amplitude loading over most of the stress range tested, but that cladding is not as important at the high stress levels.

5.4 Scatter

It is evident from Figs.4 to 7 that the scatter in life for the clad specimens was considerably less than for the unclad specimens. This would be expected in view of the fact that scatter in fatigue life has been shown by Schijve and Jacobs[16] to be associated with the initiation of fatigue cracks rather than with the crack propagation stages of fatigue life. The material used for cladding when tested alone has a fatigue performance greatly inferior to that of the core material[2], and also inferior to that of the composite aluminium alloy coated with cladding. When fatigue testing clad material the cladding is subjected to the same strain history as the core material at the root of the notch. Therefore the cladding is operating in the low scatter region of its own S-N curve. It follows that scatter is very low in the part of the fatigue life during which the fatigue process is confined to the cladding. This is likely to result in lower scatter for the clad specimens than the unclad.

In order to illustrate this an attempt was made to draw 'minimum life' curves at the lower boundary just enclosing all the test points as done previously by Kiddle[18]. The curves for the clad and unclad specimens are shown in Figs.4 and 6 and are compared in Fig.9. The similarity of the two curves implies a similarity of the 'worst' initiation conditions for both the clad and unclad specimens. This is despite the fact that the average unclad specimen takes longer to initiate a crack than the average clad specimen.

A future investigation of the scatter distributions for the clad and unclad specimens would be useful, so that a comparison could be made between them on the basis of accurate scatter factors and 'minimum' lives.

5.5 Difference in fracture mode between unclad specimens with and without a pre-stress

It was noted in section 5.3 that for the unclad specimens not subjected to a pre-stress, all the fatigue origins were from corners apart from two bore origins leading to secondary cracks, whereas approximately 25 per cent of the unclad specimens subjected to a pre-stress failed from cracks which originated from the bore.

It is not possible at this stage to give a firm explanation for this change of failure mode due to pre-stressing. However, a possible cause is that there was in the as-machined specimens a residual circumferential stress which was distributed non-uniformly along the bores of holes, the stress being most tensile at the corners. Certainly residual stresses due to machining are a well-established phenomenon[19], although measurement of their distribution was not attempted in the present programme. If there were such a stress and it were most tensile at the corners then it would be expected to induce preferential fatigue initiation there rather than in the bore. Pre-stressing would induce a more uniform residual stress along the bore and so would increase the likelihood of bore initiation.

6 PROJECTED FUTURE WORK

It is intended to extend the investigation to cover testing of clad and unclad specimens under Gaussian narrow band random loading, and programmed random loading[5], the latter representing gust loading on a transport aircraft wing. Unfortunately it is not possible to include air-ground-air cycles in the sequence. The cumulative damage performance of the two types of specimen will be studied with a view to determining the source of any errors which may be found when using Miner's rule to predict fatigue life under random loading. Particular attention will be paid to the four possible sources of error described in section 2, namely

(1) residual stresses,
(2) cycles below the initial fatigue limit,
(3) variations in relative damage rate with stress (stress dependence),
(4) stress dependent interaction.

As a part of this work the accuracy of the ESDU rule[4] will be assessed in predicting the Gaussian random and programmed random[3] fatigue life.

It is also intended to carry out an investigation into the scatter distributions of the clad and unclad specimens.

7 CONCLUSIONS

(1) The mean fatigue performance of notched (K_t = 2.3) clad specimens of 2L73 was markedly inferior to identical specimens of 2L71, the equivalent unclad material, under constant amplitude loading at a tensile mean stress. This difference was most marked at the lower stress levels where the fatigue strength of the clad specimens at 10^7 cycles to failure was only 70 per cent of the fatigue strength of the unclad specimens. The relatively poor fatigue performance of the clad specimens was attributed to early initiation in the weak cladding.

(2) It was found that the clad specimens were not as affected by residual stresses, induced by pre-stressing, as were the unclad specimens. For lives above 4×10^5 cycles the percentage increases in fatigue strength of the clad specimens due to pre-stressing were generally less than one half of those obtained on the unclad specimens. This was attributed to the fact that the cladding has a low yield point, so that under fatigue cycling of any significant alternating stress amplitude at any net mean stress the local mean stress in the cladding is always close to zero, and not greatly affected by a pre-stress. In contrast, in the unclad specimens the material at the root of the notch has a much higher yield point, and can sustain substantial local mean stresses when a net mean stress is applied. Pre-stressing may then give local yielding which reduces the local mean stress and gives a substantial improvement in fatigue strength.

(3) It was concluded from the results of the tests with pre-stressing that if the ESDU cumulative damage rule is applied to clad notched specimens and no allowance is made for yielding in the cladding, the accuracy of the rule is liable to differ from that obtained when applied to unclad specimens.

Appendix A

THE PALMGREN-MINER CUMULATIVE DAMAGE HYPOTHESIS (MINER'S RULE)[20,21]

The rule states that if any component is subjected to a variable amplitude loading sequence containing stress amplitudes σ_{aq} $(q = 1,2,3.....p)$ then the fraction of the total life used up by any single stress cycle at stress amplitude σ_{aq} is given by $\frac{1}{N_q}$, where N_q is the expected number of cycles to failure of the component under stress amplitude σ_{aq} alone.

Therefore the total fraction of the fatigue life used up by a variable amplitude waveform is

$$\sum_{q=1}^{q=p} \frac{n_q}{N_q}$$

where n_q is the number of cycles of stress amplitude σ_{aq} contained in the variable amplitude waveform. Therefore the rule predicts failure when

$$\sum_{q=1}^{q=p} \frac{n_q}{N_q} = 1 .$$

The performance of the rule is generally judged by the cumulative damage ratio

$$\sum_{q=1}^{q=p} \frac{n_q}{N_q}$$

at failure, usually shortened to $\sum \frac{n}{N}$.

This is equal to the ratio $\frac{\text{achieved life}}{\text{predicted life}}$ for random tests and for programmed tests where the number of programmes to failure is large.

Appendix B

SELECTION OF MATERIALS FOR TEST PURPOSES

The materials chosen for this investigation were BS L71 (unclad) and BS L73 (clad) being the fully artificially-aged versions of a 4 per cent copper/aluminium alloy. These were selected as being the most fatigue-critical of the copper-aluminium alloys. However since naturally-aged alloy is commonly used in areas of aircraft structure where fatigue is a problem, this type of alloy will be included in future work if possible.

The grain direction on the specimens used was longitudinal as can be seen from Fig.2. However in the pressure cabin case the dominant skin stress due to cabin pressure is at right angles to the grain direction. It is hoped that this case can be covered later in the program.

Table 1

NOMINAL CHEMICAL COMPOSITIONS AND HEAT TREATMENTS OF 2L71 AND 2L73 ALUMINIUM ALLOYS

Chemical compositions

2L71

Element	Per cent	
	Min	Max
Copper	3.8	4.8
Magnesium	0.55	0.85
Silicon	0.6	0.9
Iron	-	1.0
Manganese	0.4	1.2
Nickel	-	0.2
Zinc	-	0.2
Lead	-	0.05
Tin	-	0.05
Titanium and/or chromium	-	0.3
Aluminium	Remainder	

2L73 Core material as for 2L71
Cladding

Element	Per cent	
	Min	Max
Aluminium	99.7	-
Copper	-	0.02
Silicon	-	0.15
Iron	-	0.20
Zinc	-	0.03

Heat treatment for both alloys

1 Solution treat by heating at 505 ± 5°C quench and straighten.

2 Precipitation treat between 160°C and 190°C.

See Fig.3 for measured stress versus strain curves and tensile strength values.

Table 2

CONSTANT AMPLITUDE FATIGUE TEST RESULTS

BS271 specimens (unclad) without pre-stress

Test No.	Spec. No.	Alternating rms stress MN/m^2	Cycles to failure	Significant origins	Dominant origin
H1S	A42	60	9.72 × 10^4	2C	C
H7S	A34	60	1.05 × 10^5	2C	C
H260S	A83	60	4.20 × 10^4	2C	C
H261S	A130	60	4.88 × 10^4	4C	C
H262S	A89	60	3.65 × 10^4	2C 1B	C
H3S	A18	50	9.17 × 10^4	1C	C
H5S	A123	50	1.39 × 10^5	2C	C
H96S	A114	50	1.01 × 10^5	3C	C
H97S	A166	50	1.39 × 10^5	3C	C
H13S	A25	45	5.45 × 10^5→ (lug)	-	-
H14S	A49	45	1.89 × 10^5	1C	C
H27S	A72	45	1.26 × 10^5	1C 1B	C
H34S	A104	45	1.17 × 10^5	1C	C
H86S	A155	45	1.45 × 10^5	3C	C
H94S	A116	45	8.90 × 10^4	2C	C
H23S	A58	45	7.71 × 10^4	2C	C
H233S	A106	45	6.93 × 10^4	1C	C
H234S	A112	45	9.20 × 10^4	2C	C
H15S	A136	40	9.77 × 10^4	2C	C
H19S	A56	40	8.01 × 10^5	NA	NA
H21S	A62	40	1.00 × 10^7→	-	-
H29S	A91	40	2.16 × 10^5	1C	C
H32S	A144	40	1.00 × 10^7→	-	-
H83S	A133	40	3.11 × 10^5	2C	C
H85S	A153	40	1.00 × 10^7→	-	-
H126S	A80	39	1.21 × 10^5	2C	C
H129S	A73	39	8.20 × 10^5	3C	C
H68S	A113	35	1.00 × 10^7→	-	-
H30S	A54	35	2.26 × 10^6	NA	NA
H11S	A6	35	1.00 × 10^7→	-	-
H226S	A102	35	2.25 × 10^5	1C	C
H227S	A139	35	2.06 × 10^5	2C	C
H228S	A119	35	1.53 × 10^5	2C	C
H229S	A100	30	1.22 × 10^7→	-	-
H257S	A120	30	2.00 × 10^7→	-	-
H258S	A111	30	5.34 × 10^5	1C	C
H259S	A105	30	6.26 × 10^6	1C	C

Key: NA = not available, C = corner origin, B = bore origin, → = unbroken.

Table 3

CONSTANT AMPLITUDE FATIGUE TEST RESULTS

BS2L71 specimens (unclad) with 300MN/m^2 pre-stress

Test No.	Spec. No.	Alternating rms stress MN/m^2	Cycles to failure	Significant origins	Dominant origin
H49SX	A43	60	8.75×10^4	2C	C
H56SX	A14	60	9.80×10^4	1C	C
H70SX	A103	60	6.87×10^4	1C	C
H79SX	A143	60	7.20×10^4	1C	C
H57SX	A44	55	3.03×10^5	1B	B
H58SX	A36	55	1.59×10^5	1B 1C	B
H62SX	A35	55	9.60×10^4	2C	C
H63SX	A45	55	1.14×10^5	1B	B
H65SX	A107	55	9.32×10^4	1C	C
H92SX	A124	55	8.74×10^4	1C	C
H99SX	A59	55	1.05×10^6	1C	C
H100SX	A125	55	1.26×10^5	2B	B
H124SX	A88	52	1.18×10^5	3C	C
H128SX	A71	52	1.34×10^5	NA	NA
H132SX	A74	52	1.60×10^5	3C	C
H133SX	A84	52	2.98×10^5	2C	C
H51SX	A81	50	$9.3 \times 10^{5}\rightarrow$ (lug)	-	-
H64SX	A165	50	$1.96 \times 10^{6}\rightarrow$ (lug)	-	-
H71SX	A98	50	1.13×10^5	1C 1B	C
H75SX	A97	50	3.82×10^6	1C	C
H76SX	A77	50	1.77×10^5	2B	B
H77SX	A135	50	$1.00 \times 10^{7}\rightarrow$	-	-
H218SX	A132	45	8.80×10^5	1C	C
H219SX	A140	45	4.89×10^6	1C	C
H222SX	A147	45	2.17×10^5	1C	C
H223SX	A137	45	$2.58 \times 10^{7}\rightarrow$	-	-
H224SX	A148	45	$3.24 \times 10^{7}\rightarrow$	-	-
H225SX	A118	45	$2.00 \times 10^{7}\rightarrow$	-	-

Key: NA = not available
C = corner origin
B = bore origin
→ = unbroken

Table 4

CONSTANT AMPLITUDE FATIGUE TEST RESULTS

BS2L73 specimens (clad) without pre-stress

Test No.	Spec. No.	Alternating rms stress MN/m^2	Cycles to failure	Significant origins	Dominant origin
H4S	B96	60	6.32×10^{4}	3C	C
H6S	B111	60	6.11×10^{4}	1C 1B	B
H80S	B74	60	4.72×10^{4}	3C	C
H9S	B76	50	1.20×10^{5}	3C	C
H10S	B34	50	1.14×10^{5}	4C	C
H81S	B13	50	1.07×10^{5}	4C 1B	C
H18S	B46	45	9.40×10^{4}	3C	C
H95S	B57	45	9.80×10^{4}	3C	C
H17S	B53	40	1.60×10^{5}	4C	C
H20S	B81	40	1.27×10^{5}	4C	C
H127S	B158	39	1.66×10^{5}	2C	C
H131S	B160	39	1.53×10^{5}	2C	C
H135S	B144	40	1.14×10^{5}	3C	C
H136S	B170	40	1.00×10^{5}	3C	C
H235S	B2	40	1.22×10^{5}	3C	C
H236S	B9	40	1.00×10^{5}	3C	C
H25S	B135	30	2.91×10^{5}	2C	C
H26S	B35	30	3.11×10^{5}	1C	C
H31S	B143	30	3.61×10^{5}	NA	NA
H137S	B164	30	4.10×10^{5}	3C	C
H145S	B132	30	2.52×10^{5}	2C	C
H146S	B137	30	2.59×10^{5}	2C	C
H28S	B24	25	9.13×10^{5}	NA	NA
H33S	B3	25	9.13×10^{5}	2C	C
H78S	B7	20	$1.00 \times 10^{7} \rightarrow$	-	-
H61S	B152	20	$1.00 \times 10^{7} \rightarrow$	-	-

Key: NA = not available
C = corner origin
B = bore origin
→ = unbroken

Table 5

CONSTANT AMPLITUDE FATIGUE TEST RESULTS

BS2L73 specimens (clad) with 300MN/m^2 pre-stress

Test No.	Spec. No.	Alternating rms stress MN/m^2	Cycles to failure	Significant origins	Dominant origin
H50SX	B154	60	5.80×10^4	2C	C
H87SX	B28	60	7.50×10^4	4C	C
H93SX	B153	55	8.95×10^4	4C	C
H130SX	B159	52	1.06×10^5	2C	C
H134SX	B163	52	1.06×10^5	NA	NA
H52SX	B33	50	1.26×10^5	2C	C
H54SX	B45	50	1.09×10^5	3C	C
H98SX	B69	50	1.19×10^5	3C	C
H90SX	B86	45	1.75×10^5	4C	C
H55SX	B36	40	2.48×10^5	NA	NA
H59SX	B118	40	2.11×10^5	2C	C
H66SX	B168	40	1.78×10^5	3C	C
H91SX	B167	35	3.12×10^5	2C	C
H56SX	B97	30	8.67×10^5	1C	C
H60SX	B73	30	5.50×10^5	NA	NA
H67SX	B5	30	2.27×10^5	1C	C
H82SX	B14	30	$1.00 \times 10^7 \rightarrow$	-	-
H84SX	B23	30	5.43×10^5	3C	C
H61SX	B145	25	$1.00 \times 10^7 \rightarrow$	-	-
H214SX	B100	25	$1.80 \times 10^7 \rightarrow$	-	-
H230SX	B128	25	$1.83 \times 10^7 \rightarrow$	-	-
H231SX	B91	25	$1.08 \times 10^7 \rightarrow$	-	-

Key:
NA = not available
C = corner origin
B = bore origin
→ = unbroken

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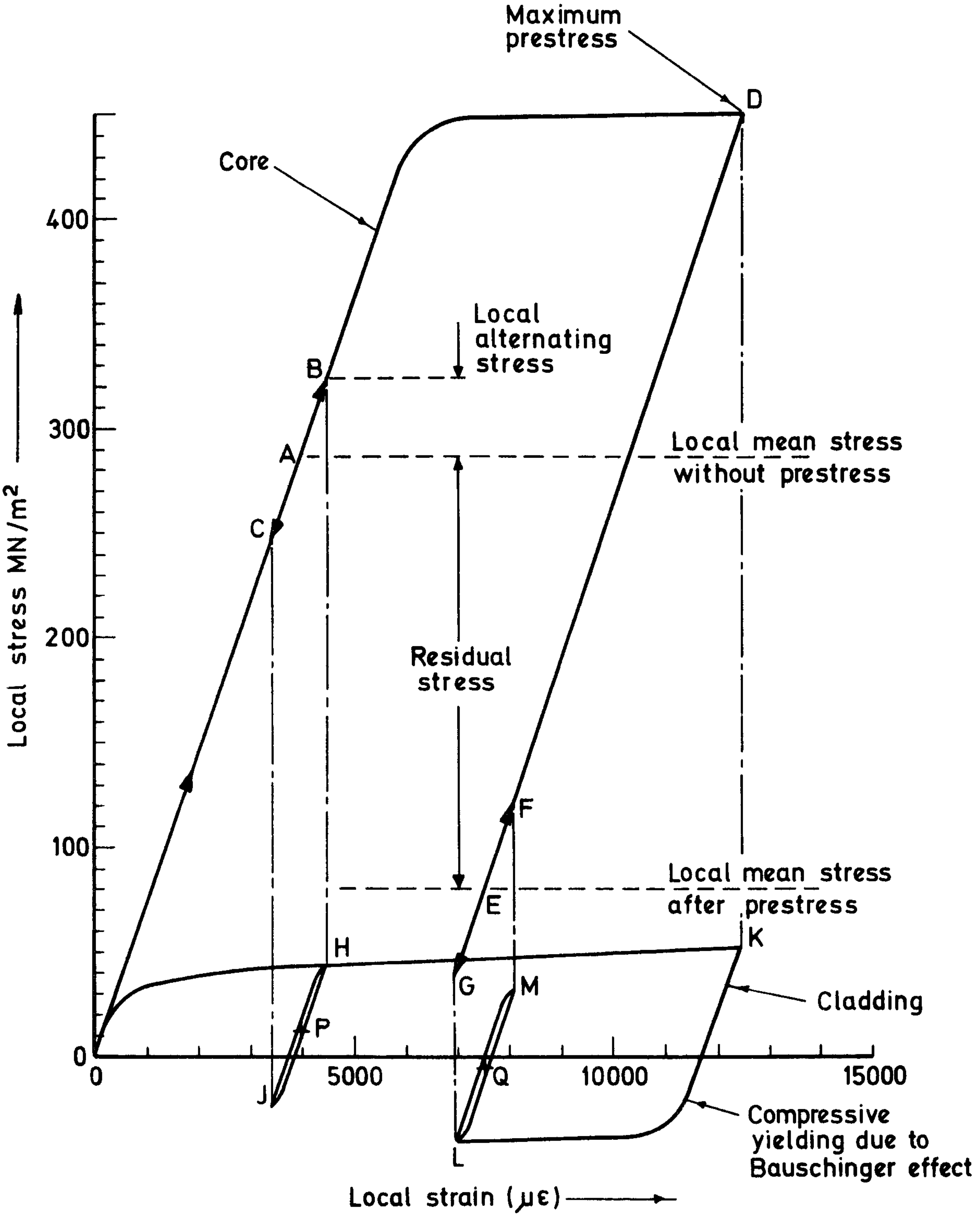
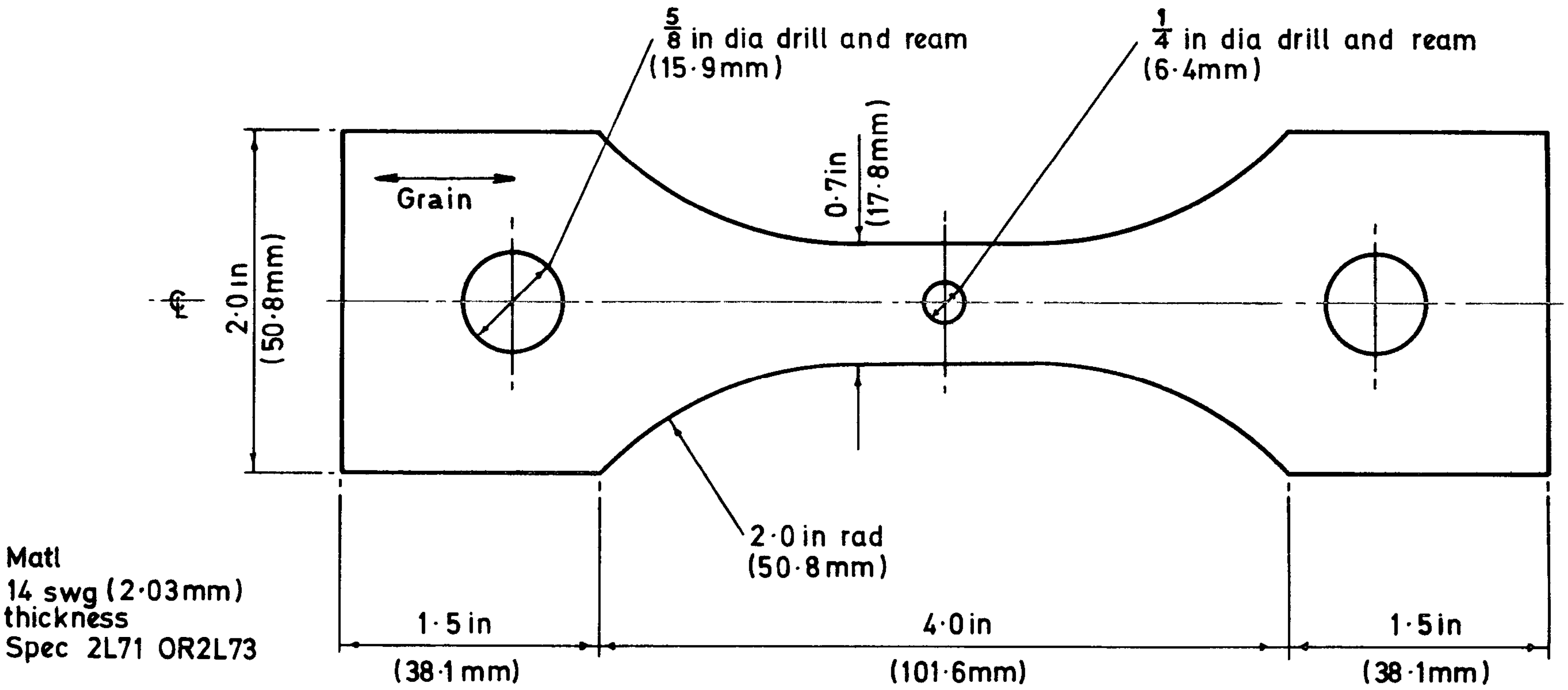
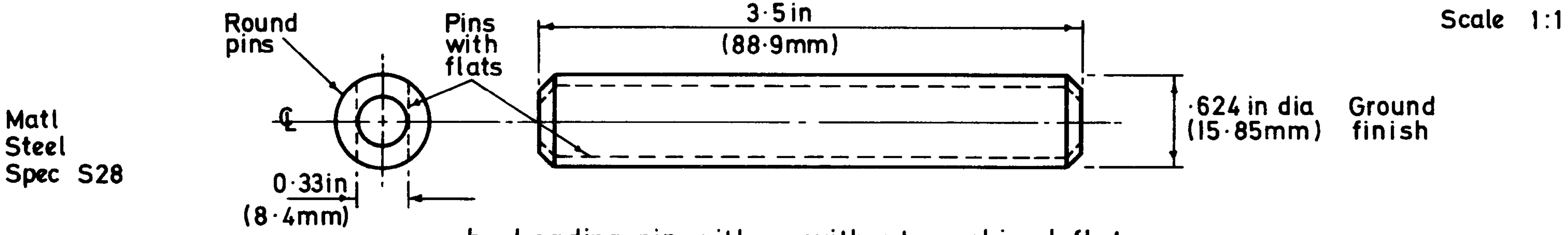


Fig.1 Stress vs strain behaviour of core and cladding at the root of a notched specimen

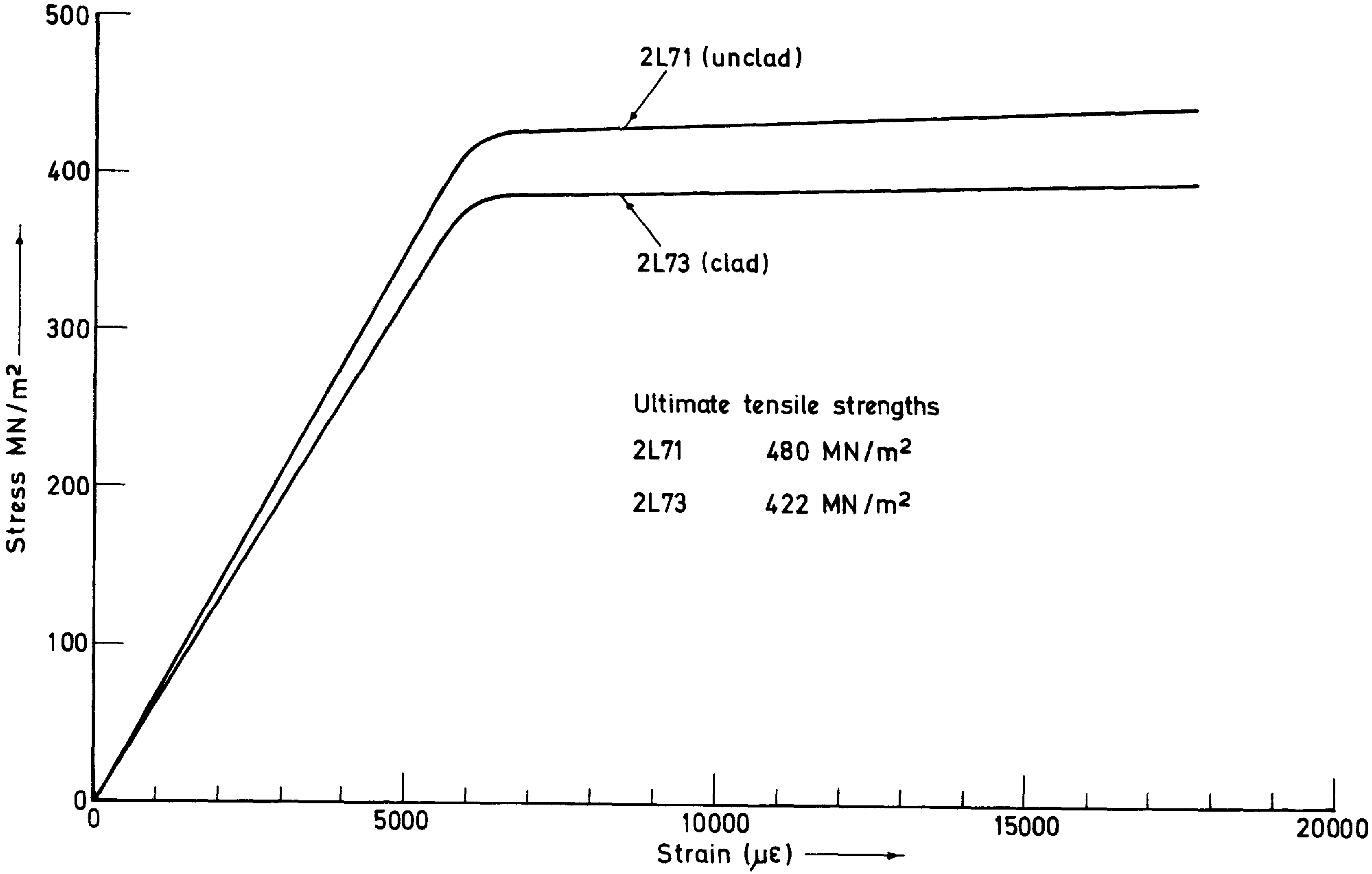


a Notched specimen $K_t = 2{\cdot}3$



b Loading pin with or without machined flats

Fig.2a&b Notched specimen and loading pins



Ultimate tensile strengths

2L71	480 MN/m²
2L73	422 MN/m²

Fig.3 Average measured stress vs strain curves for 2L71 and 2L73

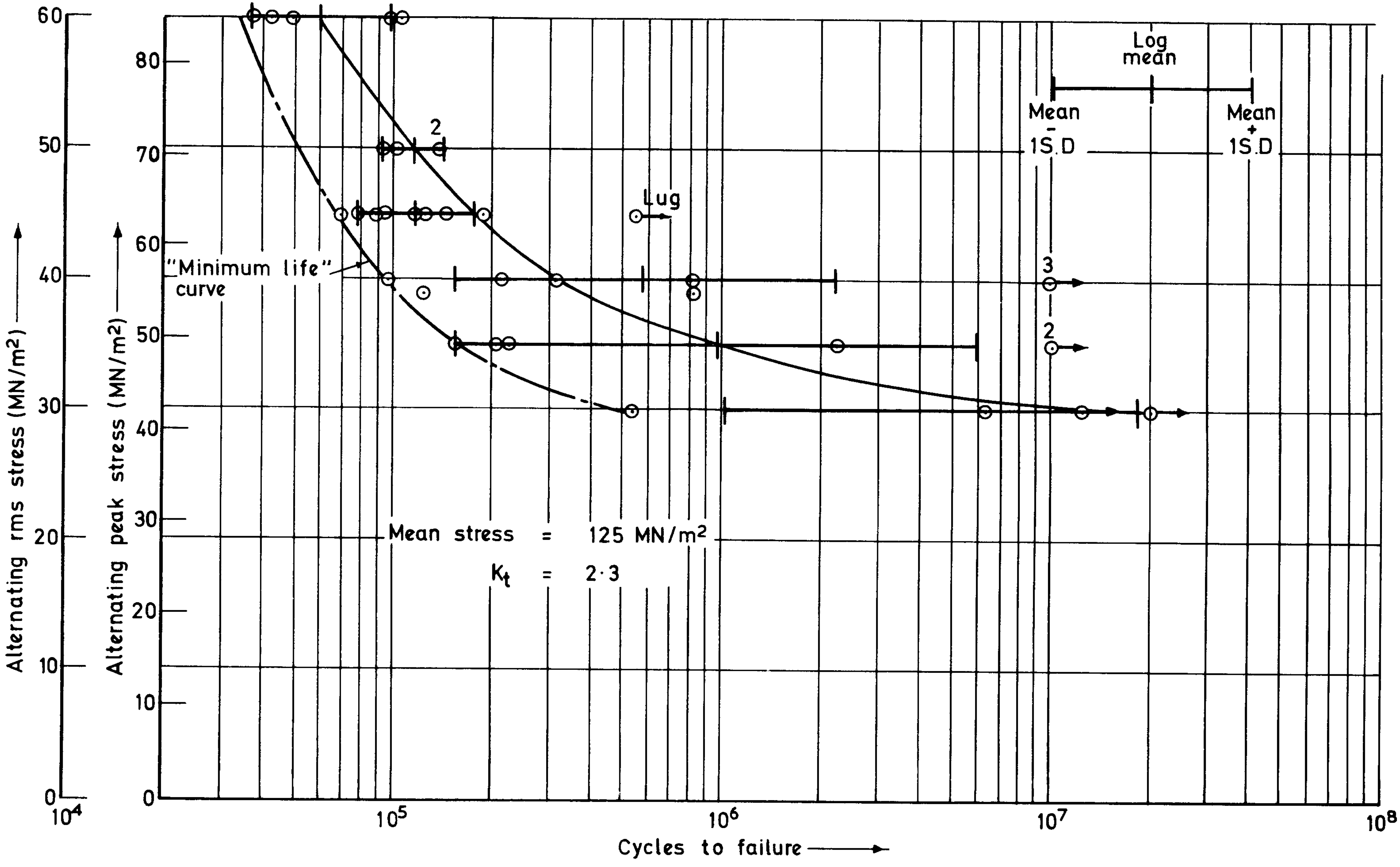


Fig.4 Constant amplitude fatigue test results without prestress
Notched specimens of 2L71 (unclad)

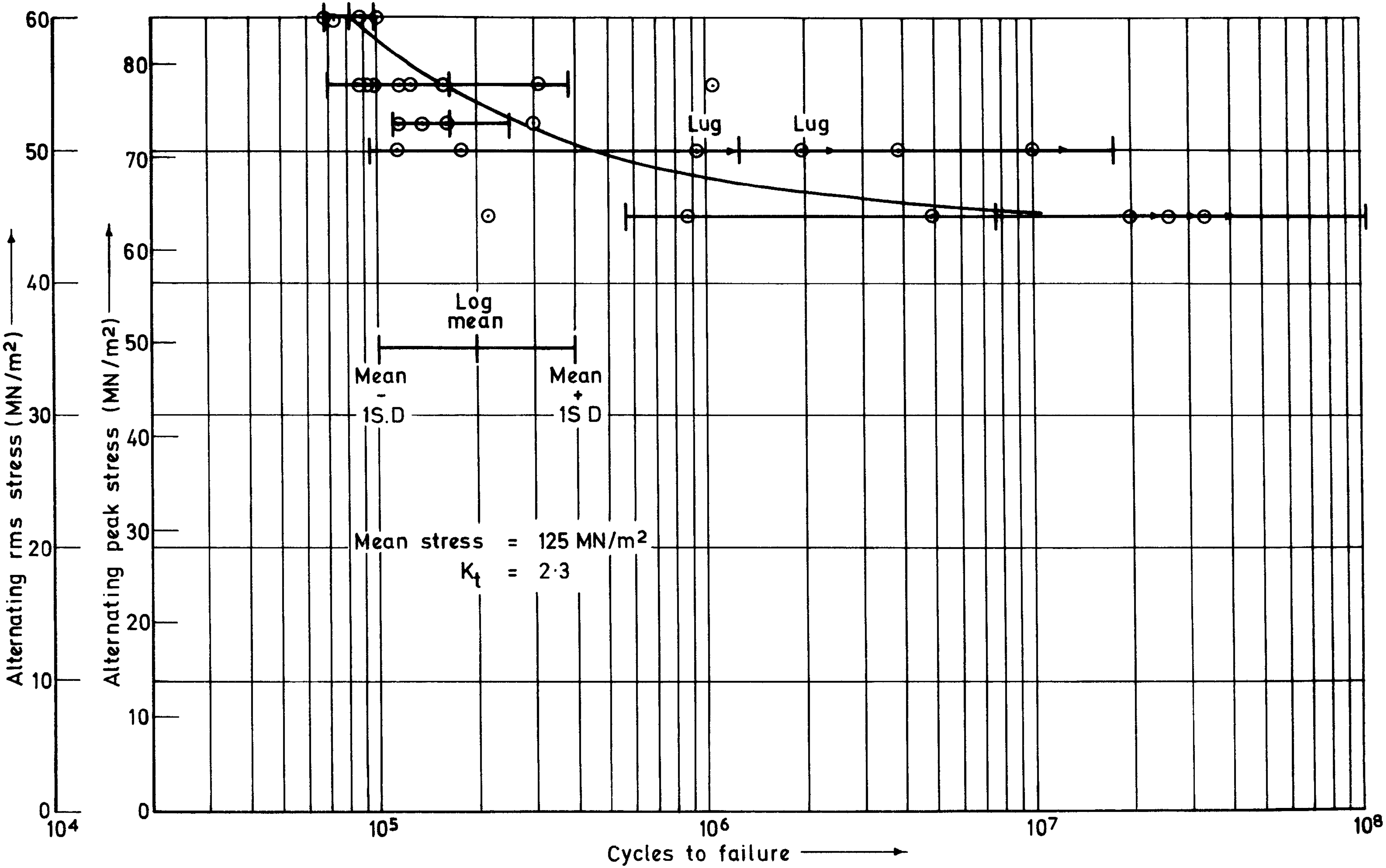


Fig.5 Constant amplitude fatigue test results with $300 MN/m^2$ prestress. Notched specimens of 2L71 (unclad)

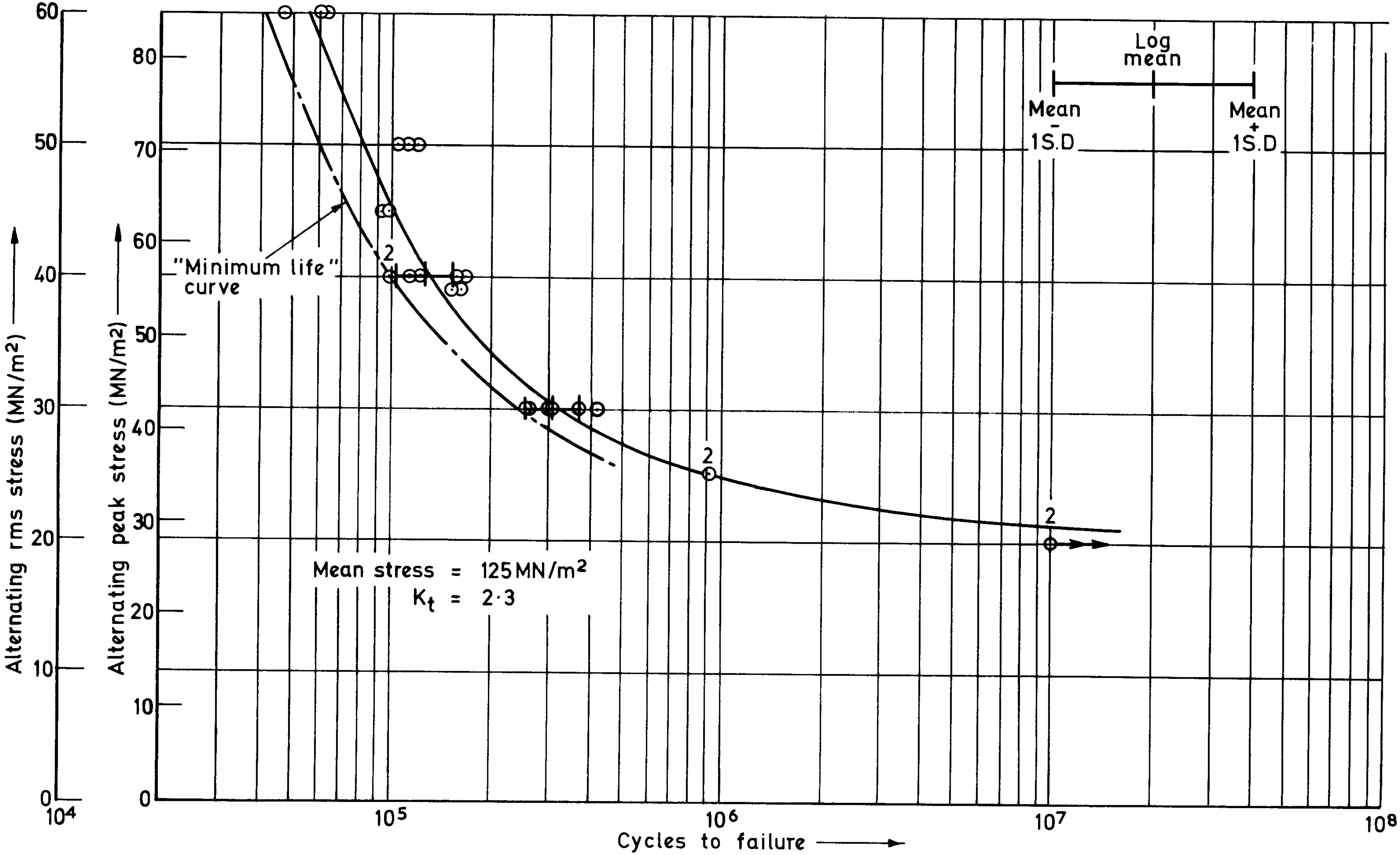


Fig. 6 Constant amplitude fatigue test results without prestress. Notched specimens of 2L73 (clad)

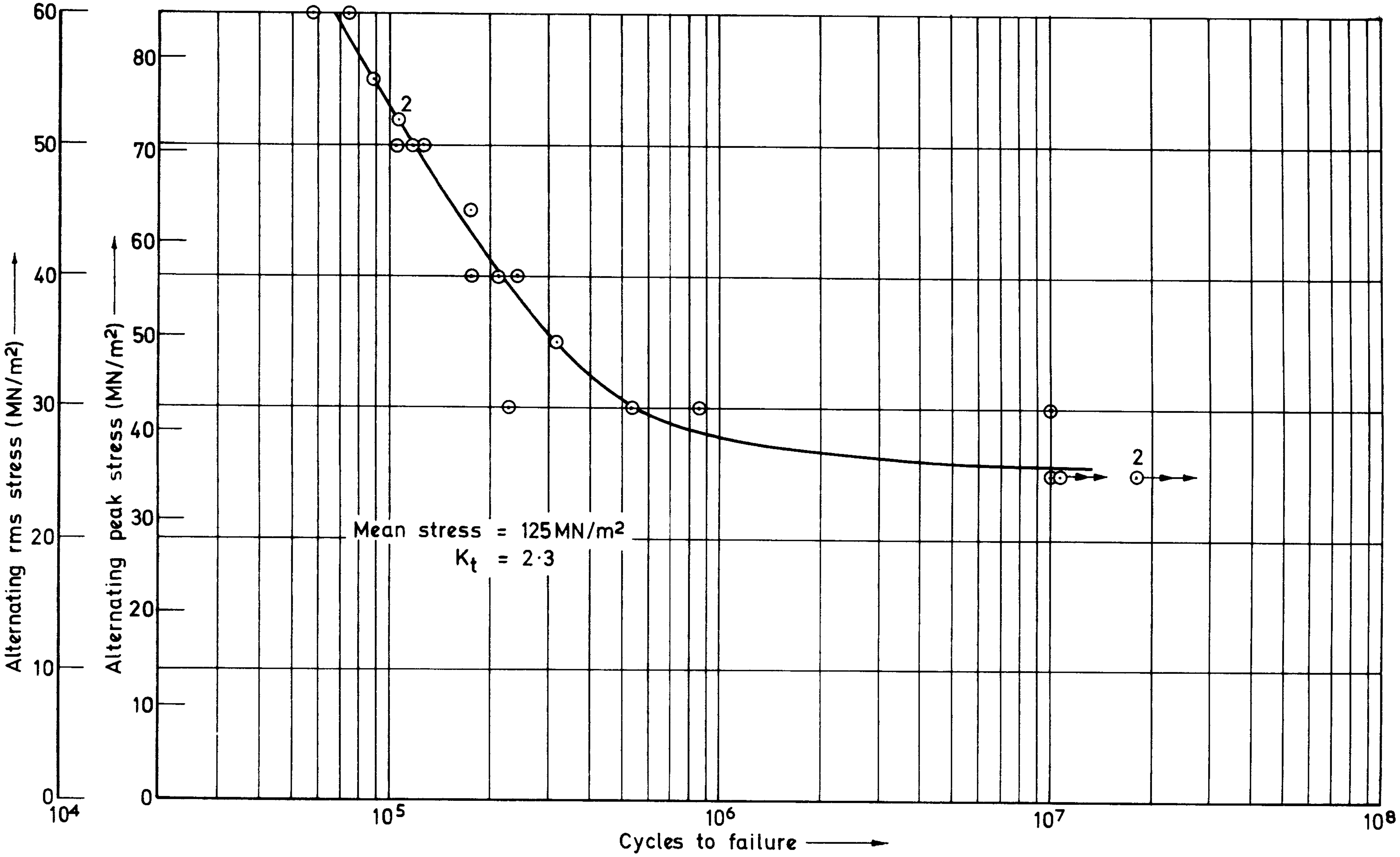
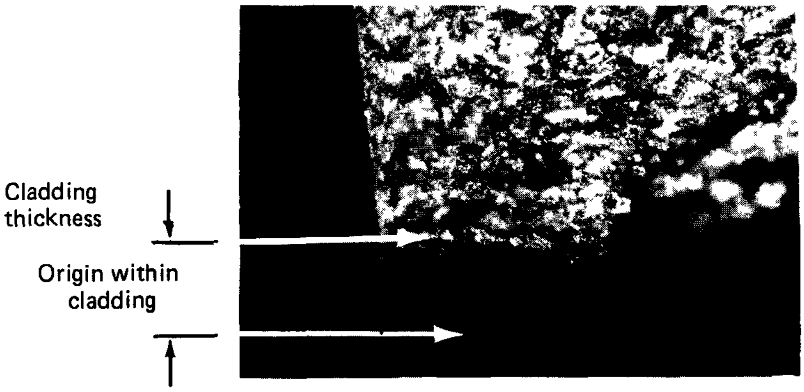
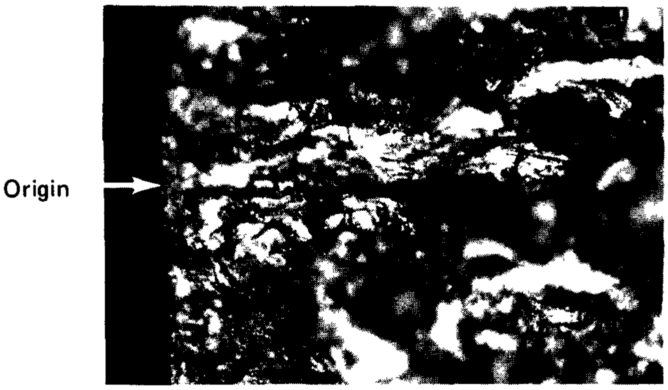


Fig. 7 Constant amplitude fatigue test results with 300MN/m^2 prestress
Notched specimens of 2L73 (clad)

a. Corner origin — unclad



b. Corner origin — clad



c. Bore origin

0.1mm

Fig.8 Typical nucleation sites

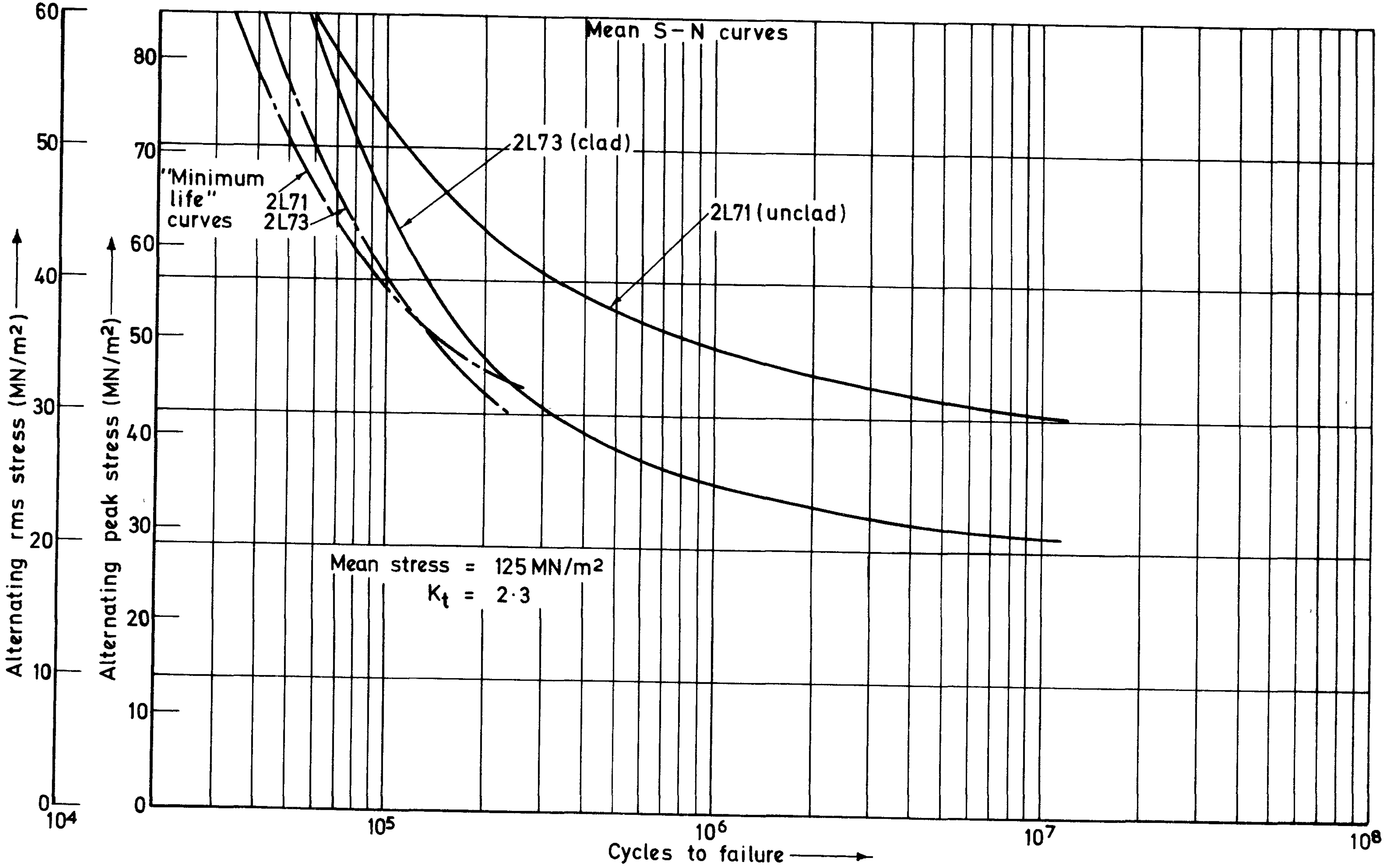


Fig. 9 Comparison of the fatigue performance of notched specimens of 2L73 (clad) and 2L71 (unclad) under constant amplitude loading

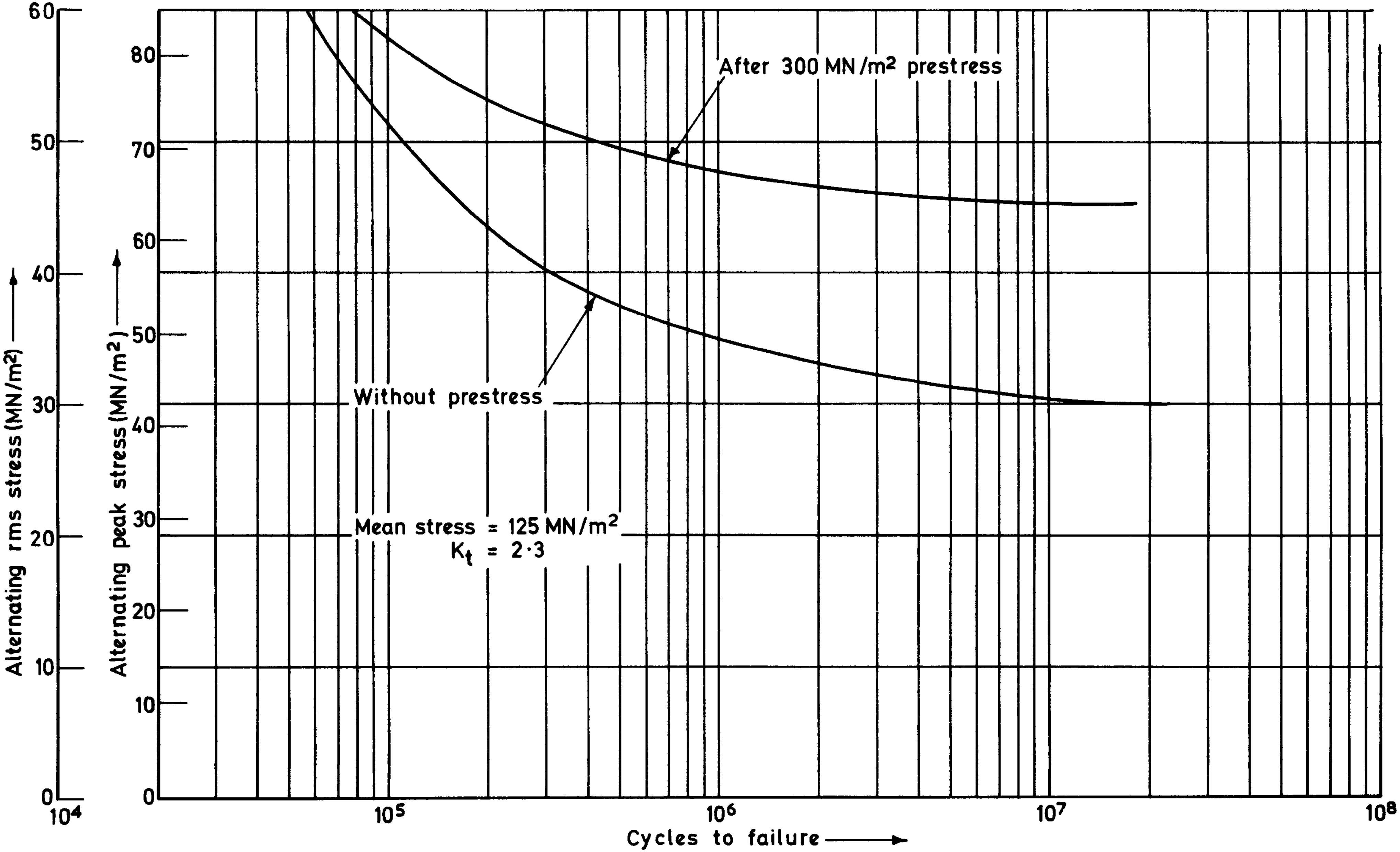


Fig.10 Effect of prestress on notched specimens of 2L71 (unclad) under constant amplitude loading

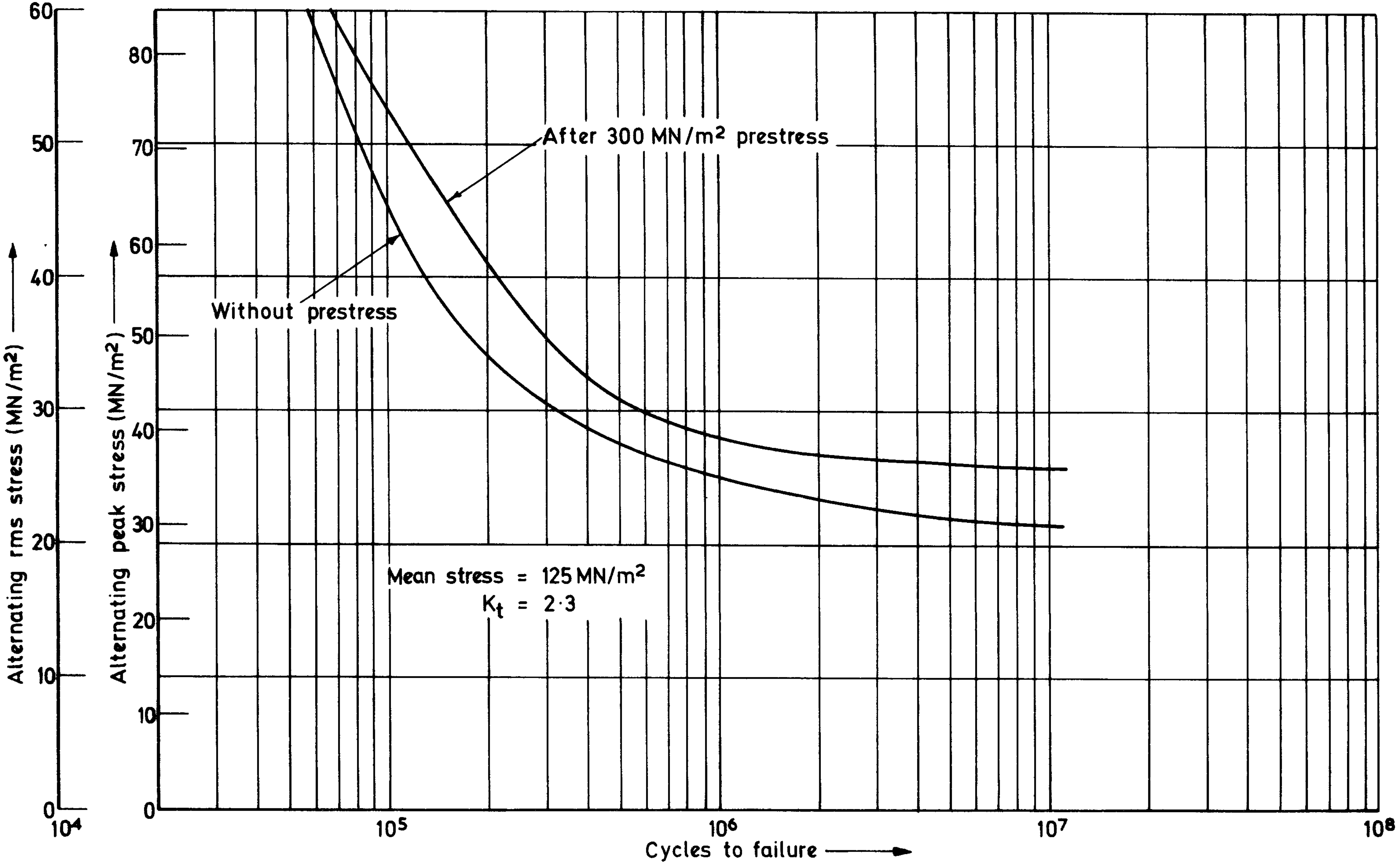


Fig.11 Effect of prestress on notched specimens of 2L73 (clad) under constant amplitude loading

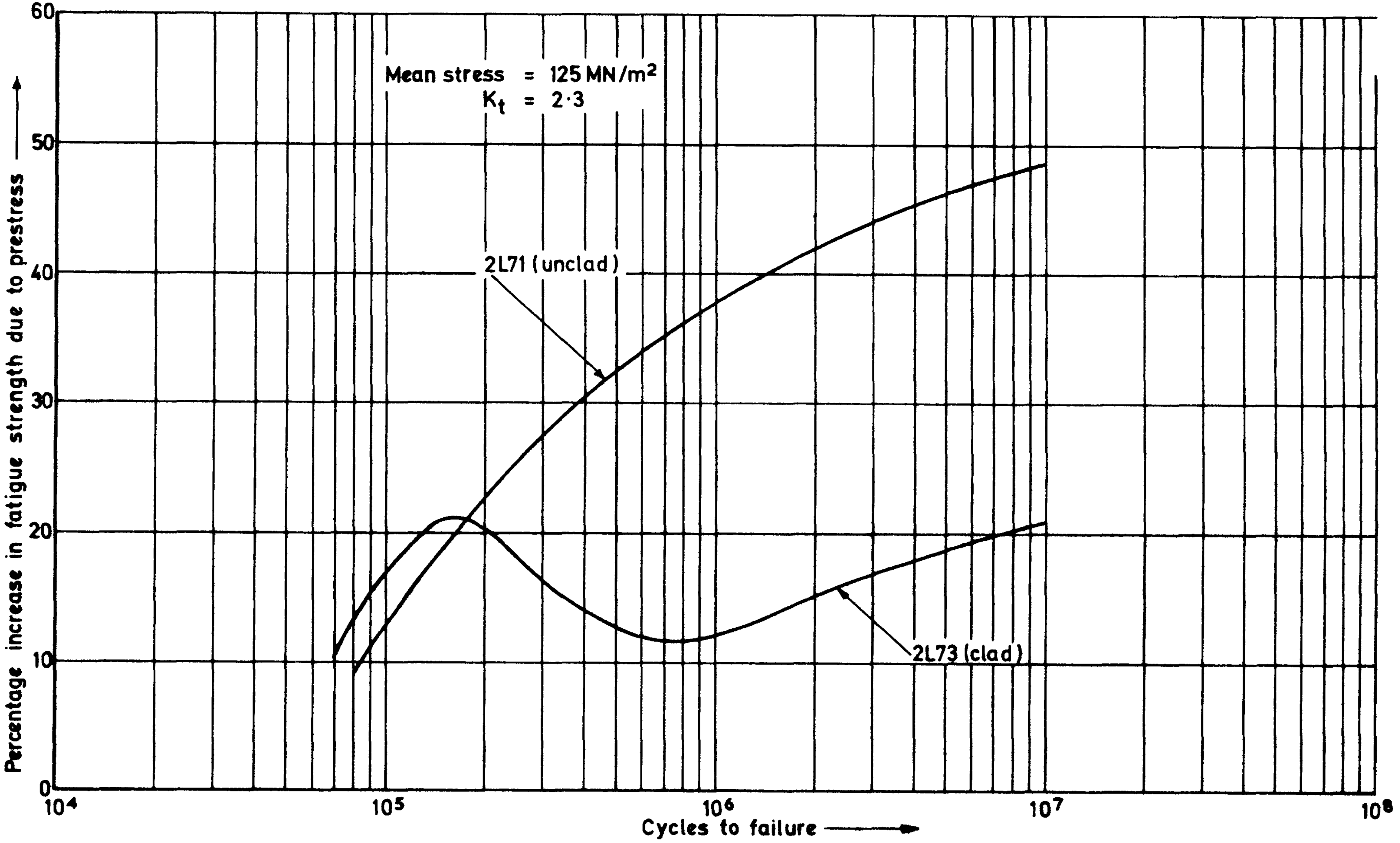


Fig.12 Increases in fatigue strength of notched specimens due to 300MN/m² prestress

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P. R. Edwards
M. G. Earl

A COMPARATIVE STUDY OF THE FATIGUE PERFORMANCE OF NOTCHED SPECIMENS OF CLAD AND UNCLAD ALUMINIUM ALLOY, WITH AND WITHOUT A PRE-STRESS

The sensitivity of 2L71 (unclad) and 2L73 (clad) aluminium alloy to residual stresses was determined by measuring the improvement in the constant amplitude fatigue strength of notched specimens due to the application of a single large tensile stress at the start of the test. It was found that the clad specimens were markedly less affected by the pre-stress than the unclad. This lack of response in the clad specimens was attributed to the low yield point of the cladding which reduced the susceptibility of this material to residual stresses.

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