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Fatigue Endurance, Crack Sensitivity and Nucleation Characteristics of Structural Elements in Four Aluminium-Copper Alloys

by

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FATIGUE ENDURANCE, CRACK SENSITIVITY AND NUCLEATION CHARACTERISTICS OF STRUCTURAL ELEMENTS IN FOUR ALUMINIUM-COPPER ALLOYS

by

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SUMMARY

Four aluminium-copper alloys in the form of notched, lug and joint specimens were tested under constant amplitude loading at ambient temperature. While there are certain differences in fatigue performance between materials, particularly in the mean endurance and scatter of notched specimens, there is little difference between the materials in terms of the minimum fatigue endurances observed. The performance of the different types of specimen are compared and conclusions are reached on the effect of fretting. The patterns of nucleation on the fatigue fracture surfaces shows that scatter in endurance is associated with the number of discrete sites of crack nucleation and that in all alloys there is a transition from single to multiple crack nucleation at a value of local stress amplitude related to the static strength. Study of fatigue crack areas at failure indicate that crack sensitivity was similar in three alloys and lower in the fourth.

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* Replaces RAE Technical Report 72107 - ARC 34195

CONTENTS

Conversions: 1000 $lb(f)/in^2$ = 6.894 $MN\ m^{-2}$ = 0.689 Hb

1 INTRODUCTION

This paper discusses the fatigue behaviour of four aluminium-copper alloys in the form of notched, lug, and joint specimens tested under constant amplitude loading at ambient temperature. The tests were conducted to provide a basis for an investigation of the effects of heat on fatigue of structural elements, some results of which have been published[1]. The present analysis, in addition to establishing the general pattern of fatigue behaviour at ambient temperature against which the effects of heat can be assessed, has shown some basic similarities in the structural behaviour of the different alloys, which are of more general interest.

The fatigue behaviour of the different alloys over a range of alternating stress are first compared in terms of fatigue endurance and it is shown that although all the alloys behave similarly when tested in the form of lug and joint specimens, there are considerable differences when in the form of notched specimens although the differences are not consistent for different stress concentrations and stress levels. However, if the alloys are compared on the basis of the minimum observed endurance, there is little difference between the alloys in any type of specimen. This is taken to indicate that endurance tends to have an extreme value distribution and that the alloys differ only in the magnitude of the scatter. Using the curves of minimum endurance the comparative behaviour of the different types of specimen is discussed. Examination of the fracture surface for the number of discrete origins of crack nucleation (or damage nuclei) and the size of the fatigue crack at failure has made it possible to compare the crack nucleation and crack sensitivity characteristics of the four alloys. The number of damage nuclei is found to be associated with fatigue stress, scatter in endurance, and material and it is established that in all the alloys there is change in the pattern of failure at a value of local stress amplitude related to the static strength. The comparison of the crack sensitivities of the four alloys shows that one alloy tends to tolerate larger fatigue cracks at failure than the other three alloys, which behave similarly.

2 MATERIALS AND SPECIMENS

Four aluminium-copper alloys were tested which had been subjected to precipitation heat-treatment nominally to maximum ultimate strength: Al 6% Cu (Hiduminium 54), DTD 5014, 2L65 and 2024-T81. The materials were obtained in the form of 12ft lengths of extruded bar of rectangular section, the Al 6% Cu being supplied by one manufacturer, the remaining materials by another. The main volume of testing was on DTD 5014 material. Table 1 gives the chemical composition of each alloy and Table 2 summarises the static tensile properties determined by tests on 113 of the 119 bars used. Each type of material was taken entirely from one melt and the extruded bars were selected so that the relatively coarse grain at the surface of the bars was shallow enough to ensure its elimination during the machining of specimens. The material was tested ultrasonically for flaws: those greater than 0.1 in were comparatively rare and were avoided in the extraction of specimens. Each bar was identified by a three digit number, the first digit signifying the material (each material was allocated two numbers, one for notched specimens and the other for lug and joint specimens) and the two remaining digits the bar number of that material. Nineteen fatigue specimens were extracted from each bar and each was identified by a five digit number, the first three digits being the bar identification number and the last two defining the position of the specimen in the bar relative to the leading end of the bar during extrusion.

Four types of fatigue specimen were used: two forms of notched specimen, a lug, and a joint. The two types of notched specimen with central holes shown in Figs.1(a) and 1(b) have theoretical stress concentrations of 2.3 and 3.4 times the average stress on the net section; for brevity they will be referred to as the 2.3 notch and the 3.4 notch. These specimens were loaded axially through lug ends by round pins on which flats were machined with the object of preventing premature failure by improving the fatigue performance of the lug.

The lug specimen in Fig.2 has two identical test sections. It was loaded axially by round pins of clearance fit (0.0016 ± 0.0010 in) and has a theoretical stress concentration of approximately 3.1.

The joint specimen shown in Fig.3 utilises the lug specimen as a centre plate. S96 steel sideplates are clamped to the centre plate by bolts which were tightened on assembly until they had extended a given amount. Extension of the bolt was determined by measuring the relative movement of 0.188in diameter steel balls set in the end faces of the bolt. An extension of 0.0020 in was applied in all cases which is estimated to give a core stress of 83000 lb/in^2, equivalent to 60% UTS; this is considered to be representative of the general level of clamping in aircraft construction. The accuracy of the extension was generally ±5%. During assembly of the joint specimen, including the bolt tightening, the components were held in a jig to achieve accurate alignment. On the assembled joint it was found that clamping pressure was transmitted from the side plate to the face of the lug over a clearly defined annular area of 0.6 in^2 around the hole corresponding closely to the size of the washers used with the bolt; the average clamping pressure over this area was 30000 lb/in^2. The outer ends of the side plates were clamped to the end fittings of the fatigue machine.

All specimen components were thoroughly degreased with an organic solvent before assembly and all test sections were dry during testing.

3 FATIGUE TESTS

All fatigue testing was at ambient temperature in fluctuating tension ($0 < R < 1$) of constant amplitude at a frequency of 33 c/s. A range of stress levels was chosen to give endurances in the range 10^5 to 2×10^7 cycles. For any given S-N curve, the mean stress was kept constant. In general the mean stress was also kept constant for each particular type of specimen, irrespective of material, except when testing Al 6% Cu, when non-standard mean stresses were used for three types of specimen. All stresses quoted are based on the cross-sectional area in the region of fatigue failure.

After failure, the fracture surfaces of the specimens were examined for two features - the number of discrete positions on the surface from which fatigue cracks emanated (damage nuclei) as indicated in Fig.4, and the areas of the fatigue crack surfaces. Fig.4 shows the disposition of the nuclei; however the surface markings by which they were identified do not show as clearly in the photograph as they do by direct observation under the microscope.

The fatigue cracks in the joint specimen nucleated at many points over a circular arc of fretting damage corresponding to the boundary of the clamping area (see unbroken ends of joint specimens illustrated in Fig.5). The consequent complexity and variability of the pattern of cracking made it impracticable to present information on crack area and number of nuclei for this type of specimen. This complexity in the pattern of cracking is shown in Fig.5 where two typical but quite different examples of patterns of failure of the joint specimen are illustrated. For comparison, an example of the consistent fracture surface of a lug specimen is also shown. It was found that the complexity and variability of the pattern of cracking in the joint specimens showed no consistent trend with endurance or stress level.

The fatigue crack surface on the notched and lug specimens consisted generally of two separate areas, one on each side of the central hole; these two surfaces were treated separately in assessing area and numbers of nuclei. Tables 3 to 18 give details of the endurances, fatigue crack areas and number of damage nuclei.

4 DISCUSSION

4.1 Outline

In the following discussion the relative fatigue endurance of the four alloys, in the various specimen configurations is first considered (section 4.2.1). Such consideration necessarily requires examination of scatter in endurance and the case is developed in section 4.2.2 for comparing the endurances on the basis of minimum lives, at each given stress level, rather than by comparing mean endurances. A comparison is then made of the differences in behaviour of the four specimen configurations (section 4.2.3).

Under section 4.3, the crack nucleation characteristics are discussed in more detail. Initially (section 4.3.1) the significance is discussed of the numbers of fatigue damage nuclei observed on the fracture surfaces as an indication of the way in which damage develops. This discussion is extended in section 4.3.2 and a pattern of behaviour is deduced which associates the number of damage nuclei with the fatigue alternating stress level and with the scatter in endurance at a particular stress level. In section 4.3.3 it is shown that the transition from single to multi origin damage nucleation in the notched specimens is related to the tensile properties of the material, and may be associated with the onset of reversed plastic cycling at the stress concentration. Finally, the significance of the fatigue crack area at failure in determining the crack sensitivity of the four alloys is discussed briefly in section 4.4.

4.2 Fatigue endurance

4.2.1 In considering how to present the information on fatigue endurance it was anticipated that four figures would be given, each one applying to a particular type of specimen and showing the S-N curves for the four materials, so that the influence of material could readily be seen. It was also intended that, for the sake of clarity, the endurance of each individual test specimen (see Tables 3 to 18) would not be plotted - each S-N curve being based on a faired line through the log mean endurance at each stress level concerned.

This approach has been adopted satisfactorily for all types of specimens in three of the materials, 2L65, Al 6% Cu and DTD 5014 alloys, for which the associated scatter in individual results, though differing between the three materials, was not unusual. These results are given for the 2.3 notch and 3.4 notch, in Figs.6 and 8. However, certain difficulties arose when presenting the results from the tests of the notched specimens in the fourth material, 2024-T81, in which the scatter was much greater. It was felt that, for these particular types of specimen, the foregoing approach would be unsatisfactory since the magnitude and nature of the scatter was such that the shape of the S-N curve could not be defined with the same degree of confidence as for the other materials and specimens. Accordingly, the individual test results for the 2.3 and 3.4 notched specimen in 2024-T81 are plotted in Figs.7 and 9 and no S-N curves are drawn.

The foregoing problem did not arise with the lug and joint specimens in 2024-T81 since the scatter was not exceptional and S-N curves could be drawn. Such curves for the lug and joint specimens are included, with those for the other three types of material, in Figs.10 and 11.

A study of the comparisons of the fatigue behaviour of the materials in Figs.6 to 11 shows differences in behaviour between the four alloys, which vary over the stress range. These differences do not show a consistent pattern for the different types of specimens tested and in fact for a given type of specimen vary over the stress range.

4.2.2 From Tables 3 to 10 it may be seen that the scatter in endurance differs appreciably with material and consequently a different picture is obtained when alloys are compared on the basis of S-N curves drawn through the lowest endurances observed at each stress level. The S-N curves of minimum endurance for all four alloys are compared for the two types of notched specimens in Figs.12 and 13 respectively, and it is seen that the differences between alloys are considerably less than was shown by comparison of the mean S-N curves. If the endurance distribution at all stress levels were log normal it could be expected that minimum endurances would become progressively lower as more specimens were tested. However, examination of the minimum S-N curve for the 2.3 notch in DTD 5014 material (Fig.14) shows that the minimum endurance at each stress level fits closely to a smooth curve despite large differences in the number of specimens tested at different stress levels.

Although this may not be significant at the high stress levels where the scatter is small, it is a strong indication that the distributions of endurance are not log-normal at the lower stresses where the magnitude of scatter is large. In Fig.15, the distributions of endurance, at high and low stress levels, are shown for all types of specimen tested in DTD 5014 material. This shows that for the notched specimens there is a marked difference between the shape of the distribution curves at high and low alternating stress levels; from plots of probability *versus* life it has been found that the distribution is approximately log-normal at high stress but that it is decidedly skewed at low stress suggestive of an extreme value distribution. In view of this it is of interest to consider the relationship between mean and minimum S-N curves in terms of standard deviation for a typical example of a notched specimen. Fig.16 shows that minimum endurance is only slightly more than one standard deviation below the mean over most of the stress range, including the highest stresses tested and rather less than one standard deviation at the lowest stress tested. This is a further indication that the distribution tends to be extremal at low stresses. It is concluded that the four alloys in notched form have very similar minimum S-N performances, that the scatter is suggestive of an extreme value distribution at low stresses, and that the alloys differ in the magnitude of the scatter.

It is generally accepted that scatter is associated with the early stages of the fatigue life leading to the initiation of cracks near the surface, rather than with the later stages of the life during which the crack propagates through the cross section[2]. This topic will be discussed generally in section 4.3 which deals with observations of the fracture surface; it is however relevant to the following discussion of the performance of lug and joint specimens which differ from that of the notched specimens particularly in that fretting tends to shorten the initiation phase of the life by rapidly producing surface damage. As a consequence of fretting, therefore, it might be expected that the endurances of both lug and joint specimens would show less scatter than the endurances of notched specimens. This is shown to be so (Tables 11 to 18), especially at low stresses. The S-N diagrams of mean endurance for the lug specimen (Fig.10) and the joint specimen (Fig.11) show little difference between the alloys, which in view of the relative short initiation phase, suggests no great differences in crack propagation characteristics. In Fig.10 the S-N curves for lug specimens of three of the alloys are virtually identical; the difference between these three curves and that for Al 6% Cu is possibly associated with the lower mean stress used for the latter. For joint specimens (Fig.11), all alloys tend to behave similarly, including the Al 6% Cu despite the different mean stress employed. It would appear therefore that the fatigue performance of the bolted joint is insensitive to the composition of the Al-Cu alloys tested. A similar conclusion was reached by Heywood[3] for large multi-bolt joints in comparing Al-Cu and Al-Zn alloys. However, it would appear that this result is not necessarily applicable to all high strength aluminium alloys, as the results of tests[4] on joint specimens similar to those used in the present work but with thicker side plates showed a marked difference between 2L65 and an experimental alloy Al 5% Mg 4% Zn 1% Mn alloy. As a consequence of the low scatter in endurance of lug and joint specimens a comparison of the minimum S-N curves (Figs.17 and 18) does not affect the conclusions reached above.

4.2.3 It has been seen that differences between materials are small for all types of specimen if the minimum S-N curve is used as a basis for comparison. It is possible therefore to make an overall assessment of the relative behaviour of the four types of specimen by comparing S-N bands of minimum endurance containing all materials. It is seen in Fig.19 that these bands are quite narrow: ±25% on endurance for notched specimens and less for lug and joint specimens. The superiority of the 2.3 notch over the 3.4 notch at the same nominal stress is associated with slower crack initiation due to the smaller local value of alternating stress, it being presumed that the crack propagation phases are similar. It is deduced from this that the convergence between bands with decreasing stress is an indication that a decreasing proportion of endurance is spent in crack initiation. The performance of the lug specimen ($K_t = 3.1$) can be assessed in relation to the notched specimen if one may disregard differences in geometry and load transfer; on this basis an approximate idea of the effect of fretting on the lug specimen is that it reduces life by factors ranging from 4 at the higher stresses to 7 at the lower stresses. The larger effect of fretting at low stresses may seem surprising in view of the previous deduction that in notched specimens a smaller proportion of the life is spent in initiation at the lower stresses. However, this indicates that fretting is more effective at shortening the crack initiation phase at low amplitudes; this is in line with observations made by Schijve and Jacobs[5]. The performance of the joint specimen, despite clear evidence of damage initiation by fretting, is comparable with that of the notched specimens at low stresses and is superior at the higher stresses. It is difficult to assess the degree of stress concentration from theoretical considerations, but comparison of its fatigue strength with that of the lug specimen (again neglecting obvious differences in geometry and loading actions) suggests, on average, a stress concentration factor of about 1.4. A similar value was deduced in other work[6] using similar specimens.

4.3 Crack nucleation

Having compared the fatigue behaviour of the alloys and the types of specimen on the basis of endurance, we will now examine further aspects of comparative behaviour by studying the evidence of the pattern of crack nucleation from observations of the fracture surfaces.

4.3.1 As described in an earlier report[1], it was found possible to recognise on the fracture surface the discrete positions at the notch from which fatigue cracks emanated (Fig.4) and which were termed damage nuclei; observation of the variation in the numbers and positions of nuclei indicated the way in which damage developed. This proved useful in the development of a basic model by Stagg[7] for the discussion of scatter in fatigue. It is postulated that the positions of nuclei are dictated by the existence of chance defects in both the microstructure of the material and the surface finish of the specimen, and the orientation of these defects in relation to the applied stress. These chance defects are distributed across the test section of the specimen and cracks nucleate at different defects sequentially. For nominally identical specimens there will be scatter in the fatigue life due to the different distribution of these sites and their level of sensitivity, i.e. different sites will require different levels of stress and time under fluctuating stress for the nucleation of a crack. Thus the total number of nuclei which develop will depend on the fatigue stress level as this dictates the number of sites which are capable of developing into damage nuclei. However the total number of damage nuclei to develop will also depend on the speed at which cracks spread from the earliest nuclei to appear. If crack growth is slow compared with crack nucleation there is an opportunity for a large number of nuclei to develop; if cracking is comparatively fast the crack growing from the first nucleus may spread across the test section before other nuclei appear. Later in this section it will be shown that in fact it is possible to associate the number of damage nuclei with stress, scatter in endurance and material.

Before discussing the observations on damage nuclei it is necessary to consider the significance of the numbers of nuclei which are present on the fatigue crack surfaces on each side of the test section: these surfaces will be referred to as the major and minor fatigue crack areas according to their relative size. It will be assumed that the earliest nuclei led to the growth of the major crack and are a more significant measure of the onset of cracking than the nuclei in the minor area whose subsequent appearance would be hastened by the already growing major crack. In the following discussion of damage nuclei, therefore, only those in the major area will be considered.

4.3.2 First, consider variation in the number of nuclei with alternating stress for nominally identical specimens. Fig.20, for the 3.4 notch in DTD 5014 material, is typical of the trend for notched specimens in all alloys. At the lowest stress giving failure there is invariably one nucleus. As stress increases there is an increasing tendency for more than one nucleus to appear on the fracture surface; the average number of nuclei increases continuously with stress amplitude and at the same time scatter in the number of nuclei increases. For lug specimens the trend is similar but due to the influence of pin-bending on the bearing of the pin in the hole, the corners of the hole are the most highly stressed regions and therefore two nuclei often occur.

What is the significance of the increasing numbers of nuclei as alternating stress is increased and endurance reduces? When alternating stress is increased it would be expected that crack initiation and propagation would speed up. An increase in the number of nuclei with alternating stress implies that crack initiation speeds up more than crack propagation because, as was discussed earlier, for a large number of nuclei to appear crack growth must be slow compared with crack nucleation. The implication is therefore that nuclei are developing with increasing rapidity and with a consequent shortening of the nucleation phase which contributes to the reduction in endurance. In addition to the effect on mean endurance, it can be expected that increasing numbers of nuclei will be associated with reduced scatter in endurance for the following reasons. The greater the number of potential sites of nucleation, the less scatter there will be in the time under fluctuating stress for the first nucleus to develop. Also there will be less scatter in the growth of the crack when large numbers of nuclei appear as the mode of cracking will be more consistent. In Fig.21, the estimated standard deviation of log endurance has been plotted against the average number of nuclei for notched and lug specimens. The mean trend shows that as the average number of nuclei increases from one to two, scatter in endurance reduces to a low value and remains constant at higher numbers. It might be supposed that scatter would continue to fall as the number of nuclei increased but another factor, which tends to oppose this, is the increased scatter in numbers of nuclei as the mean number increases (see Fig.20).

Although we have seen that increasing numbers of nuclei are associated with reduced endurances, once a few nuclei are present the generation of further nuclei cannot be expected materially to affect the fatigue endurance. This is illustrated in Fig.22 which is a typical example of the influence of the scatter in numbers of nuclei on the endurance at a particular stress level. This shows sufficient correlation between numbers of nuclei and endurance to account for some of the scatter in endurance. The shape of the average curve supports the argument that the earliest nuclei have the greatest influence on endurance.

As stated in section 3, it was not practicable to present information on crack area and numbers of nuclei for the joint specimen, but in general, it was observed that the fatigue crack initiated from many damaged nuclei. The values of standard deviation for joint specimens in Tables 15 to 18 are similar for all materials and stress levels; this would be expected for failures from many nuclei as was seen in Fig.21 for notched and lug specimens. On average the scatter for joints is larger than for lugs, possibly due to variability in the pattern of failure.

4.3.3 In the foregoing discussion it has been seen that with increasing alternating stress there is an increase in the average number of nuclei and that the transition from single to multiple nuclei is accompanied by a marked reduction in the scatter in endurance. This transition in the mode of failure has been noted in various materials by a number of investigators. Work by Williams and Taylor[8] on steels, brass and aluminium alloys, tested in rotating bending, indicated that a clearly defined transition in the mode of failure was associated with a discontinuity in the S-N curve. The transition stress was thought by Williams and Taylor to be significant in representing the fatigue limit of the core material; this is higher than the conventional fatigue limit which is governed by surface conditions. A similar association between the discontinuity and transition in the mode of failure can be observed in the work of Marco and Starkey[9] on an aluminium-zinc alloy and SAE 4340 steel alloy tested in rotating bending. Also, differences in the distribution of endurance at stresses above and below the transition have been noted by Cicci[10] and Swanson[11] for maraging steel and aluminium alloy respectively. Swanson, using axial loading, found that the transition occurred over a wide range of stress unlike the well-defined transition observed in the tests using rotating bending described above. These observations by other investigators viewed in conjunction with those of the present work indicate that transition in mode of failure is an important characteristic of fatigue behaviour and may provide a further basis for comparing the fatigue performance of different materials. The transition from single to multiple nuclei observed in the present investigation occurred over a wide range of stress, like that observed by Swanson. The number of specimens is sufficiently large to provide quite accurate curves of the change in average numbers of nuclei with alternating stress (Figs.23 to 25) and in the following paragraph a criterion is suggested which facilitates the comparison of the transition in the different alloys.

When considering earlier the variations in standard deviation and the average number of damage nuclei, it was seen that as the average number of nuclei increased from 1 to 2, scatter in endurance reduced to a low value and remained virtually constant at higher numbers (Fig.21). Thus, in increasing from one to two nuclei, there is a change in the distribution of the endurances as noted by Cicci[10] and Swanson[11]. Referring again to Fig.21 it would seem appropriate to regard the transition stress as that value of the alternating stress for which, on average, two nuclei are present on the fracture surface. For notched specimens, values of the transition stress were obtained from the curves of Figs. 23 and 24 and are given in Table 19. This criterion is inapplicable to lug specimens which often exhibit two nuclei at the lowest stresses used (see Fig.25) due to the influence of pin-bending on the bearing of the pin in the hole.

The transition stress was found by Williams and Taylor[8] to be proportional to the conventional 'fatigue limit' (fatigue strength at 10^7 cycles) of the material and they suggest that the transition stress is a measure of the fatigue limit of the core material. If this is so, it might be expected that both the conventional fatigue limit and the transition stress are associated with the tensile properties of the material. In Fig.26, the values of transition stress from Table 19 are plotted against the UTS of the materials. The plotted points agree reasonably well with lines representing a constant ratio between the calculated local stress amplitude at the root of the notch and the UTS of the material; the values of this ratio are 0.48 for the 2.3 notch and 0.39 for the 3.4 notch. A similar correlation was obtained with proof stress (Fig.27) and, as is shown later, this may point to a physical explanation of the mechanism governing the transition.

Correlation was also attempted between UTS and the fatigue limits for the three alloys whose fatigue limit could be estimated from the mean S-N curves of Figs.6 and 8. In this case the values of the ratio between the calculated local stress amplitude and the UTS of the alloy were about 0.21 for both types of notch in the three alloys. It may therefore be concluded that both the conventional fatigue limit and the transition stress are associated with the tensile properties of a material.

Mention has been made of the work of Williams and Taylor[8] which suggested that for plain specimens there is a simple relationship between the fatigue limit and the transition stress. They stated that this relationship could be extended to notch specimens; in this case the ratio between the two was thought to be equal to the stress concentration factor, K_t. However, the largest value of K_t reported which gave close agreement with this relationship was 2.0. Using the results reported here, the transition/fatigue limit ratio was calculated to be 2.28 for the 2.3 notch and 1.86 for the 3.4 notch. It is therefore concluded that the simple relationship between the conventional fatigue limit and the transition stress as suggested by Williams and Taylor is not generally true for all values of stress concentrations.

A more convincing explanation of the transition from single to multiple nucleation and its correlation with the tensile properties of the material may lie in the association of the transition with the onset of reversed plastic yielding at the root of the notch. Edwards[13] has shown that after tensile yield, local compressive yielding occurs at a stress concentration when the local stress has reduced to approximately zero during the subsequent unloading and while the net stress is still tensile. It has also been found that the greater the extent of the tensile yielding, the less the local stress reduces during subsequent unloading before compressive yield commences. Therefore, in the present tests in which the local stress cycle is constrained at its upper end by tensile yield, it can be expected that reversed plastic cycling will occur at a local stress range approximately equal to the value of the tensile yield stress, i.e. an amplitude of about half the yield stress. The actual ratios of transition stress to 0.1% proof stress averaged for the four materials were 0.56 for 2.3 notch and 0.45 for the 3.4 notch (see Fig.27) which are not too far from the expected value but which are different for the two values of stress concentration. However this difference can be explained qualitatively on the basis that the 3.4 notch experienced a greater tensile yield strain and therefore the reversed yielding occurred at an earlier stage of the unloading.

4.4 Area of fatigue crack at failure

A comparison of the sensitivity to cracks of the notched and lug specimens in the different alloys is possible in terms of the proportion of the fracture surface which was cracked by fatigue at final failure. The test section of a specimen consists of equal areas on each side of a hole (Fig.4); in general, fatigue cracks will grow on both sides of the hole though not necessarily symmetrically, and it can be seen that the degree of symmetry depends on the stress level in the test. The fatigue crack areas at failure are designated, according to their relative size, the major fatigue crack area and minor fatigue crack area. The first nucleus to develop leads to earlier crack development on one half of the test section and it is assumed that this half develops into the major fatigue crack area.

The variation in the fatigue crack areas at a given fatigue stress is similar for all four alloys; typical examples are shown in Fig.28 for a 2.3 notch and a lug, and illustrate the striking differences between the two types of specimen. For notched specimens, the major and minor areas vary considerably, the tendency being for both the areas to influence the final failure. By constrast, on the lug specimen the major area tends to be constant, the minor area varying considerably and apparently having little influence on the final failure. This difference in the failure characteristics of the notched and lug specimens is reflected in the size of the fatigue crack area at final failure which for the lug is a much larger percentage of the original area than for the notch at the same peak value of net stress. The large variation in major and minor areas at failure in the notch specimens is largely due to the irregularity of the crack front. Failure is caused by a combination of the loss in cross sectional area due to the fatigue crack and the maximum length and position of the fatigue crack from the notch surface. Fatigue crack areas in lug specimens are more regular in shape than in notched specimens and consequently they vary less in size. They also tend to be larger due to the particular loading conditions; Cartwright and Spencer[14] have shown that the residual static strength of a cracked element is larger for the same size crack when the element is loaded from inside the hole (i.e. lug specimen) than when it is loaded away from the hole (i.e. notched specimen). Thus on the basis of fracture mechanics it would be expected that for the same static strength, the fatigue crack area would be larger for a lug than for a notch specimen.

Some differences between the materials are found in the average variation in the major, minor and total fatigue crack areas with the peak stress of the fatigue loading cycle (Figs.29 to 34). In general, with increasing stress there is a decrease in major area and an increase in minor area, resulting in increasing symmetry of failure about the notch. The increasing magnitude of the minor area with stress sometimes results in an increase in total area. In general, Al 6% Cu tends to have a larger fatigue crack at failure than the other three alloys, which all behave similarly.

The general relationship between residual static strength and fatigue crack area is the subject of a report[15] on further work in this programme.

5 CONCLUSIONS

A comparison has been made of the fatigue performance of four aluminium-copper alloys in the form of notched, lug and joint specimens loaded in fluctuating tension at constant amplitude. The following conclusions were drawn:-

(a) Differences between the alloys were appreciable when comparing the mean endurances of the notched specimens but were not appreciable for lug or joint specimens. However, differences between alloys were small for all types of specimen if minimum fatigue endurances were considered.

(b) For notched specimens, the magnitude of the scatter differed in the four alloys and the scatter was suggestive of an extreme value distribution at low stresses. For the lug and joint specimens, scatter was comparatively small.

(c) Comparison of the performance of the four types of structural elements tested, gave an approximate indication that fretting in the lug specimen effectively reduced life by factors ranging from 4 at the higher stresses to 7 at the lower stresses, and that the stress concentration in the joint was equivalent to a K_t of about 1.4

(d) The average number of damage nuclei which occurred on the fatigue crack surface increased with alternating stress level for all alloys. At a given alternating stress, endurance tended to vary inversely with the number of damaged nuclei.

(e) Scatter in endurance was associated with the average number of nuclei. As this number increased from one to two, scatter in endurance reduced to a relatively low value and at higher numbers of nuclei the scatter remained constant.

(f) For each type of notched specimen, the local stress amplitude at which there was transition from single to multiple cracking was proportional to the tensile strength of the material. A similar correlation was obtained with local stress amplitude at the fatigue limit; this relationship was the same for both types of notched specimen. It was considered that this transition could correspond with the onset of reversed plastic cycling at the root of the notch.

(g) A comparison of the crack sensitivity of the four alloys showed that one alloy tended to tolerate larger fatigue cracks at failure than the other three alloys, which behaved similarly.

Table 1

CHEMICAL COMPOSITIONS

	DTD 5014	2L65	2024-T81	Al 6% Cu
Element	Percentage by weight			
Cu	2.33	4.45	4.27	6.02
Mg	1.64	0.75	1.60	0.24
Si	0.15	0.73	0.18	0.12
Fe	1.07	0.38	0.31	0.29
Mn	0.08	0.48	0.56	0.23
Zn	0.09	0.15	0.13	0.04
Ni	1.28	-	-	0.01
Ti	0.03	0.05	0.04	0.15
Cr	-	0.13	-	-
Al	Remainder	Remainder	Remainder	Remainder

Table 2

SUMMARY OF STATIC TENSILE PROPERTIES

Material	No. of specimens tested	Mean 0.1% P.S. lb/in^2	Estimated standard deviation of 0.1% P.S.	Mean U.T.S. lb/in^2	Estimated standard deviation of U.T.S.
DTD 5014	84	55350	1160	62830	837
2L65	18	63660	2010	72130	1800
2024-T81	18	70110	2690	77530	1590
Al 6% Cu	13	54430	1660	66390	1200

Table 3

FATIGUE TEST RESULTS - NOTCH K_t = 2.3 DTD 5014

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 16000	16601	0.398	15	1c+2	13	1c+2	0.105
"	16605	0.581	15	2c	3	2c	
"	16610	0.300	26	1	1	2c+1	
"	16615	0.497	25	2c+3	16	5	
"	16619	0.377	29	1c+2	9	2c	
"	18201	0.357	17	9	13	2c+11	
"	18215	0.307	68	9	2	2c+14	
18000 ± 15000	18216	0.296	52	2c+12	17	1c	
18000 ± 14000	11701	0.701	36	2c+1	17	1c	0.083
"	11705	0.552	34	2c	1	1c	
"	11710	0.649	40	1c+1	1	1c	
"	11715	0.664	37	1c	16	1c	
"	11719	0.432	31	1c	1	1c+1	
"	12301	0.705	35	1c	8	2c	
"	12305	0.728	50	1c+2	23	3	
"	12310	0.600	41	2c	0	0	
"	12315	0.694	65	2c+1	1	1c	
"	12319	0.754	52	1c	17	2c	
"	13701	0.701	43	1c	11	2c	
"	13705	0.676	35	2c	6	2c	
"	13710	0.671	42	1c	22	2c	
"	13715	0.549	36	2c	1	2c	
"	13719	0.683	59	2c	47	2c+1	
"	14301	0.720	39	1c+3	22	2	
"	14305	0.817	45	2c	25	2c	
"	14310	0.809	43	2c	9	2c	
"	14315	0.427	41	1c+2	4	2c+3	
"	14319	0.640	42	1c+4	2	1c+1	
"	14601	0.651	37	2c	8	1c	
"	14605	0.503	48	2c	14	1c+4	
"	14609	0.823	38	2c	0	0	
"	14615	0.751	45	2c	14	1c	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 3 (continued)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 14000	14619	0.614	32	2c	3	1c	
"	15101	0.621	74	2c	2	1c	
"	15105	0.619	38	1c	3	1c	
"	15110	0.491	58	1c+1	1	1c	
"	15115	0.604	42	1c	1	1c	
"	15119	0.650	44	1c	1	1c	
"	15401	0.813	32	1c	5	1c	
"	15405	0.712	56	2c	8	2c	
"	15409	0.680	60	1c	5	2c	
"	15415	0.758	52	1c	0	0	
"	15419	0.701	41	2c	14	2c	
"	17101	0.644	61	2c+1	21	1c+1	
"	17105	0.524	42	2c+1	1	1c+1	
"	17110	0.603	43	2c+2	10	1c	
"	17116	0.424	48	3	7	2c	
"	17119	0.706	65	1c+1	1	1c+2	
"	17402	0.865	48	1c+1	0	0	
"	17406	0.406	45	1c	1	1c	
"	17410	0.891	57	1c	28	1c	
"	17415	0.804	46	2c	2	2c	
"	17419	0.918	59	2c+1	9	2c	
"	17901	0.604	35	2c+1	35	1c	
"	17905	0.625	51	1c	10	2c	
"	17910	0.698	49	2c	42	2c	
"	17915	0.400	48	2c+1	1	2c	
"	17919	0.567	40	2c	12	2c	
"	18202	0.859	17	1c+1	3	1c+1	
"	18205	0.900	52	2c+1	35	1c+1	
"	18701	0.536	15	1c	8	3	
"	18705	0.586	29	3	8	1c	
"	18710	0.539	27	1c+1	20	1	
"	18715	0.570	22	1c+1	14	3	
"	18719	0.601	26	1c+2	1	1c	
"	19001	0.644	57	1c+2	1	1	
"	19005	0.734	56	1c+1	12	1c+1	
"	19010	0.613	60	3	13	1c+1	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 3 (continued)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 14000	19015	0.770	40	1	9	1c	
"	19019	0.552	65	1c+4	32	2c+3	
"	19201	0.733	20	1c+1	1	2	
"	19205	0.594	22	1c+1	3	2	
"	19210	0.639	26	1c+2	24	1c	
"	19215	0.534	23	1c+4	17	1c+2	
"	19219	0.580	22	2c+8	12	8	
18000 ± 13000	18208	0.722	66	1c+3	19	2c+1	
18000 ± 12000	12313	1.10	56	2c	0	0	0.297
"	15106	0.887	47	1c	12	2c	
"	16206	4.63	60	1	0	0	
"	18203	1.21	19	1c	8	1	
"	18218	0.622	36	1c	5	1c+2	
"	19002	1.29	48	1	0	0	
18000 ± 11000	18212	0.974	40	1c+2	39	1c	
18000 ± 10000	12302	1.45	48	1c	0	0	0.238
"	15118	0.941	57	1c	0	0	
"	16218	1.51	43	1c	0	0	
"	17118	1.30	48	1c	1	1c	
"	18206	2.35	48	1c	15	1c	
"	18209	4.47	32	1c	0	0	
18000 ± 9000	10601	61.5UB	-	-	-	-	0.119**
"	10602	1.90	37	1c	1	1c	
"	10605	1.81	40	1c	0	0	
"	10610	1.82	33	1c	0	0	
"	10615	1.63	39	1c	0	0	
"	10618	1.85	34	2c	0	0	
"	11201	1.36	38	1c	1	1c	
"	11205	2.34	44	1c	0	0	
"	11207	2.04	39	1c	0	0	
"	11210	3.59	38	1c	2	1c	
"	11211	1.49	44	1c	0	0	

UB = Unbroken

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

** Standard deviation calculated using J.S. Lariviere's method[12].

Table 3 (continued)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 9000	11215	2.11	37	1c	0	0	
"	11219	1.18	36	1c	2	1c	
"	13201	2.03	37	1c	0	0	
"	13205	1.64	42	1c	0	0	
"	13210	1.95	35	1c	1	1c	
"	13215	1.70	47	1c	0	0	
"	13219	2.34	42	1c	0	0	
"	16201	1.75	48	2c	0	0	
"	16205	2.08	39	1c	1	1c	
"	16210	1.95	38	1c	0	0	
"	16215	2.31	37	1c	0	0	
"	16219	1.66	55	1c	10	1c	
"	16701	1.55	43	2c	0	0	
"	16705	2.26	43	1c	1	1c	
"	16710	1.28	45	1c	0	0	
"	16715	1.74	40	1c	1	1c	
"	16718	2.13	38	1c	14	1c	
"	16719	28.4^{UB}	-	-	-	-	
"	17001	2.34	34	1c	0	0	
"	17006	2.07	39	1c	0	0	
"	17010	2.14	37	1c	0	0	
"	17015	2.28	40	1c	0	0	
"	17019	1.34	35	2c	0	0	
"	18207	3.00	29	1c	0	0	
"	18211	3.41	35	1c	0	0	
"	18219	2.19	43	1c	0	0	
18000 ± 8000	12306	1.62	38	1c	0	0	0.886**
"	15113	1.64	46	1c	0	0	
"	15402	1.80	45	1c	0	0	
"	17106	2.08	41	1c	0	0	
"	18204	207^{UB}	-	-	-	-	
"	18213	65.9	35	1c	0	0	
18000 ± 7000	12318	3.73	62	1c	0	0	
"	16202	5.78	44	1c	0	0	
"	17902	2.61	41	1c	25	1c	
"	17906	3.19	47	1c	36	2c	
"	18210	205^{UB}	-	-	-	-	
"	19006	143^{UB}	-	-	-	-	

UB = Unbroken

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

** Standard deviation calculated using J.S. Lariviere's method[12].

Table 3 (concluded)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 6500	17913	4.01	50	1c	1	1c	
18000 ± 6000	17102	5.89	50	1c	0	0	
"	17918	3.54	49	1c	0	0	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 4

FATIGUE TEST RESULTS -

NOTCH K_t = 2.3 2L65

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 16000	20103	0.529	60	1c+1	1	2c	0.052
"	21001	0.581	54	2c	1	1c	
"	21005	0.536	38	1c	7	2c	
"	21010	0.575	43	1c	1	1	
"	21015	0.618	45	2c	0	1c	
"	21019	0.657	46	1c	1	1	
"	21101	0.582	57	3	16	1c	
"	21105	0.413	45	1c+2	1	1c+1	
"	21110	0.545	42	1c	0	0	
"	21115	0.542	58	1c+3	12	2c	
"	21119	0.603	67	1c+1	0	0	
18000 ± 15000	20112	0.808	42	1c	20	1c	-
18000 ± 14000	20102	0.888	43	1c	1	1c	-
"	20113	0.540	41	1c	1	1c	
18000 ± 13000	20114	0.901	43	1c	0	0	-
"	21102	1.10	48	1	11	1c+1	
18000 ± 12000	20101	1.32	41	1c	0	0	0.174
"	20116	1.02	42	1c	3	1	
"	21701	1.01	40	1c	0	0	
"	21705	1.20	42	1c	0	0	
"	21710	1.53	38	1c	0	0	
"	21715	1.44	43	1c	0	0	
"	21719	2.55	37	1c	0	0	
"	22202	2.77	34	1c	0	0	
"	22207	1.82	44	1c	1	1c	
"	22211	2.91	52	1c	0	0	
"	22215	2.22	36	1c	18	1c	
"	22218	2.62	45	1c	0	0	
18000 ± 11000	20115	0.832	45	1c	9	1c	-
"	21107	1.16	48	1c	0	0	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 4 (concluded)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 10000	20105	2.57	56	1c	0	0	0.227
"	20117	0.916	41	1c	0	0	
"	21702	1.77	42	1c	0	0	
18000 ± 9000	20118	79.3^{UB}	-	-	-	-	-
"	20119	1.75	49	1c	0	0	
"	21113	19.5	53	1c	0	0	
"	21707	2.85	46	1c	0	0	
18000 ± 8000	20104	2.76	42	1c	1	1c	0.324**
"	21118	3.50	41	1	0	0	
'	22101	5.54	48	1c	37	1c	
"	22105	4.67	43	1c	0	0	
"	22110	3.50	44	1c	0	0	
"	22115	6.16	55	1c	2	1c	
"	22118	5.22	51	1c	4	1c	
"	22201	17.7	47	1c	2	1c	
"	22205	31.2^{UB}	-	-	-	-	
"	22210	190^{UB}	-	-	-	-	
18000 ± 7000	20107	52.5^{UB}	-	-	-	-	-
"	21713	4.15	46	1c	0	0	
"	21718	10.8	47	1c	1	2	
"	22217	204^{UB}	-	-	-	-	
18000 ± 6000	20106	156^{UB}	-	-	-	-	-

UB = Unbroken.

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

** Standard deviation calculated using J.S. Lariviere's method[12].

Table 5

FATIGUE TEST RESULTS -

NOTCH K_t = 2.3 2024-T81

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 16000	30101	0.484	39	1c	2	1c	0.169
"	30105	0.554	46	1c+4	23	1c+2	
"	30110	0.439	62	2c	1	2	
"	30115	0.450	45	2c+1	1	1c	
"	30119	0.575	38	1c	12	2c	
"	30905	0.684	40	2c	13	1c	
"	31405	0.835	32	1c	0	0	
"	31410	1.19	49	2c	0	0	
"	31413	1.33	33	1c	0	0	
"	31419	0.782	33	1c	0	0	
18000 ± 15000	30913	0.565	43	1c	1	1c	-
18000 ± 14000	30106	0.882	34	1c	12	1c	0.380
"	30903	0.978	47	1c	0	0	
"	31806	8.79	38	1c	0	0	
"	31807	2.32	42	1c	16	1c	
"	31810	2.39	34	1c	0	0	
"	31815	2.40	50	1	0	0	
"	31818	1.95	37	1c	0	0	
"	32003	1.72	36	1c	0	0	
"	32010	9.01	35	1c	0	0	
"	32015	2.02	39	1c	0	0	
"	32019	3.39	45	1c	0	0	
18000 ± 13000	30914	1.04	35	1c	0	0	-
"	30919	0.742	53	1c	1	1c	
18000 ± 12000	30102	1.48	42	1	0	0	-
"	30901	1.22	46	1c	11	1c	
"	31418	1.63	42	1c	0	0	
"	31805	26.7	48	1c	0	0	
"	32006	122^{UB}	-	-	-	-	
18000 ± 11000	30915	1.27	42	1c	0	0	0.694
"	30918	0.922	47	1c	0	0	
"	31402	17.0	48	1	0	0	

UB = Unbroken.

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 5 (concluded)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 10000	30113	3.61	43	2c	0	0	-
"	30902	1.55	49	1c	1	1c	
"	32002	56.1^{UB}	-	-	-	-	
18000 ± 9000	30118	1.94	47	1c	14	1c	0.542
	30916	2.13	48	1c	0	0	
	30917	17.6	43	1c	0	0	
18000 ± 8000	30906	2.64	56	1c	10	2c	-
	32005	26.2^{UB}	-	-	-	-	-
18000 ± 7000	30904	4.78	53	1c	0	0	-
18000 ± 6000	30907	6.12	55	1c	1	1c+4	-
18000 ± 5000	30912	120^{UB}	-	-	-	-	-

UB = Unbroken

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 6

FATIGUE TEST RESULTS - NOTCH K_t = 2.3 Al 6% Cu

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 15000	40301	0.382	63	4	12	2	0.084
"	40702	0.403	45	3	13	2	
"	40716	0.546	53	1	36	1c+5	
18000 ± 14000	40105	1.06	58	1c+2	6	1	0.144
"	40110	0.555	65	1c+3	55	1	
"	40203	0.525	59	4	9	1	
"	40209	0.741	36	1c+1	27	1	
"	40306	0.751	65	1c	8	1	
"	40307	0.747	72	1c+2	4	1	
"	40804	0.582	51	3	47	3	
"	40901	0.648	44	4	42	2	
"	41009	0.512	41	1	38	3	
"	41010	0.404	43	4	34	2	
"	41013	0.352	49	6	17	2	
"	41015	0.593	38	1c+3	35	3	
"	41113	0.381	50	3	18	3	
"	41114	0.363	30	2	17	2	
"	41208	0.378	47	1c+3	34	2	
"	41212	0.358	52	5	28	5	
18000 ± 13000	40101	0.740	71	1	11	1	0.126
"	40217	0.604	60	1	0	0	
"	40917	1.07	67	1	7	1	
18000 ± 11000	40216	3.94	80	1	14	1	0.280
"	40318	2.39	59	1	0	0	
"	40819	1.79	65	1c	4	1	
"	40916	1.27	70	1	0	0	
18000 ± 9000	40316	46.4	69	1	0	0	0.752
"	40317	32.2	70	1	0	0	
"	40902	1.84	77	1c	1	1	
"	40904	2.06	78	1c	9	1	
18000 ± 7000	40319	197^{UB}	-	-	-	-	-

UB = Unbroken

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 7

FATIGUE TESTS RESULTS -

NOTCH K_t = 3.4 DTD 5014

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 10,000	17302	0.492	52	1c+15	42	1c+9	0.053
"	17310	0.431	62	2c+30	49	2c+27	
"	17315	0.515	49	1c+12	48	17	
"	18302	0.378	43	1c+15	38	1c+12	
"	19118	0.430	65	1c+12	54	1c+11	
18000 ± 9000	11901	0.537	57	1c+8	47	8	0.068
"	11905	0.481	40	1c+6	16	1c+9	
"	11910	0.583	48	2c+6	34	1c+4	
"	11915	0.571	58	1c+7	44	1c+9	
"	11919	0.464	50	11	27	8	
"	12203	0.662	50	5	37	5	
"	12207	0.621	41	4	18	5	
"	12801	0.619	58	8	34	2c+8	
"	12805	0.501	52	1c+11	38	2c+8	
"	12810	0.535	50	1c+12	45	2c+13	
"	12815	0.483	46	2c+11	37	1c+14	
"	12819	0.492	41	2c+13	35	2c+11	
"	14201	0.628	59	1c+10	38	1c+6	
"	14205	0.554	41	2c+13	40	6	
"	14210	0.464	41	16	17	9	
"	14215	0.563	52	12	29	1c+7	
"	14219	0.614	48	5	33	1c+3	
"	17301	0.866	40	1c+7	35	1c+7	
18000 ± 8000	10201	0.945	63	1c+5	5	1c+10	0.090
"	10205	0.782	52	1c+4	37	5	
"	10210	0.735	55	4	31	2	
"	10215	1.12	59	6	25	1c+10	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 7 (continued)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 8000	10219	0.987	61	1c+4	25	1c+3	
"	10801	1.18	45	1c+7	8	9	
"	10805	1.11	37	1c+3	36	3	
"	10810	1.10	33	1c+3	30	1c+1	
"	10815	1.44	40	1c	11	9	
"	10819	1.24	44	1c+2	24	1c+3	
"	11301	1.22	54	2c+3	38	2c+6	
"	11305	1.27	71	2c+3	24	1c+9	
"	11310	1.36	48	2c+6	39	2c+10	
"	11315	1.34	70	2c+3	2	1c+5	
"	11319	1.03	43	1c	37	2c+2	
"	12204	1.45	41	1c+1	29	1c+4	
"	12219	1.11	44	1	29	1c+1	
"	13301	1.18	62	4	41	1c+7	
"	13305	1.35	46	1c+3	5	1c+3	
"	13310	1.46	39	2	9	1	
"	13315	1.19	40	1c+2	30	2c+4	
"	13319	0.911	49	1c+5	5	2c+6	
"	15001	1.74	41	2	21	1c	
"	15005	1.17	44	1c+1	19	1c+5	
"	15011	1.01	49	1c+2	32	1	
"	15015	1.06	55	2c+2	2	8	
"	15018	1.14	33	2c	27	1c+2	
"	15901	1.12	43	1c	36	2c	
"	15905	1.08	59	2c	21	1c	
"	15910	1.06	45	1c	31	1c	
"	15915	1.08	75	2c+3	6	1c+1	
"	15919	1.10	42	1c	9	2	
"	16501	0.760	54	19	21	16	
"	16505	1.09	42	1	25	1c+5	
"	16510	0.849	63	12	30	1c+9	
"	16515	1.03	61	2c+8	54	12	
"	16519	1.11	60	2c+9	1	1c+2	
"	16801	1.28	54	1c+4	19	1c+6	
"	16805	1.78	38	2c	14	2c+6	
"	16810	1.58	63	1c+2	56	6	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 7 (continued)

Average stress on net area lb/in^2	Specimen No.	Endurance 10^5 (N) cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 8000	16815	1.37	48	1c+1	30	2c+4	
"	16819	1.33	39	1c	39	3	
"	16901	0.935	36	1c+9	30	1c+6	
"	16905	0.904	61	1c+4	33	1c+3	
"	16910	0.773	46	5	16	1c+15	
"	16915	0.695	59	10	44	1c+8	
"	16919	1.18	73	2c+7	16	9	
"	17201	1.24	61	2c+6	49	2c+5	
"	17205	1.07	43	2c	31	1c+1	
"	17210	1.46	63	1c+2	2	10	
"	17215	1.03	43	3	30	2	
"	17219	1.27	40	1c	39	1c	
"	17303	1.19	32	1c+1	23	1c+1	
"	18301	1.72	39	1c	38	1	
"	18305	1.28	41	1c	33	1c	
"	18310	1.25	47	2c	44	2	
"	18315	1.27	46	1c+1	12	10	
"	18319	1.24	45	5	11	1c+1	
"	19101	1.00	63	2c+6	48	2c+9	
"	19105	0.995	39	1c+3	33	2c+9	
"	19110	0.979	53	1c+3	28	1c+2	
"	19115	0.878	47	1c+2	34	1c+3	
"	19119	1.13	66	1c+8	24	1c+5	
"	19501	0.647	70	1c+11	20	18	
"	19505	1.09	72	1c+7	1	4	
"	19510	0.950	46	9	42	1c+12	
"	19515	0.992	53	2c+12	19	6	
"	19519	1.11	55	10	9	7	
18000 ± 7000	12217	1.90	63	1c+1	0	0	0.064
"	12218	1.55	44	1	2	2	
"	17304	2.17	44	2c	0	0	
"	18318	1.56	45	1c	38	1c	
"	19102	1.93	50	1c+6	46	1c+3	
"	19113	2.14	41	1c+1	2	3	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 7 (continued)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 6000	12205	3.16	40	1c	0	0	0.225
"	12212	3.25	50	1c	6	1	
"	17305	9.00	55	1c	3	1	
"	17311	2.44	41	1c	39	1	
"	18313	2.03	49	1c	41	1c	
"	19106	2.99	44	1c	17	1c	
18000 ± 5500	17306	2.96	43	1c	1	1c+2	
18000 ± 5000	14701	4.87	45	1c	2	3	0.337**
"	14705	3.80	38	1c	31	1c	
"	14711	4.38	52	1c	47	1c	
"	14715	5.52	55	1c	1	4	
"	14718	5.31	47	1c	3	3	
"	15501	17.5	44	1c	1	2	
"	15502	4.73	45	1c	1	1c+2	
"	15505	8.81	42	1c	1	1c+1	
"	15507	4.42	42	1c	29	1c	
"	15510	11.2	49	1c	1	1c+2	
"	15514	4.34	52	1c	1	1c+2	
"	15519	4.20	42	1c	30	1c	
"	17312	4.74	81	2c	0	0	
"	17313	4.81	55	1c	16	1c+3	
"	17801	7.63	59	1c	0	0	
"	17802	28.2	19	1c	1	1c+4	
"	17805	4.58	42	1c	0	0	
"	17806	5.24	52	1c	1	1c+2	
"	17810	6.13	47	1c	38	1c	
"	17811	212^{UB}	-	-	-	-	
"	17815	28.1	46	1c	1	1c+1	
"	17818	68.5	46	1c	1	2	
"	17819	16.3	46	1c	0	0	
"	18601	4.23	44	1	1	1c	
"	18605	4.94	43	1c	1	1c	
"	18610	5.54	51	1c	6	1	
"	18615	6.07	43	1c	1	1c+2	
"	18618	5.51	57	1c	3	1c+2	
"	18619	102^{UB}	-	-	-	-	
"	19401	11.2	48	1c	1	4	
"	19405	5.12	50	1c	1	1	

UB = Unbroken

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

** Standard deviation calculated using J.S. Lariviere's method[12].

Table 7 (concluded)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 5000	19410	3.77	49	1c	29	1c	
"	19415	4.26	49	1c	1c	1c	
"	19419	3.33	49	1c	34	1c	
18000 ± 4000	15002	228^{UB}	-	-	-	-	
"	15007	9.95	50	1c	0	0	
"	17307	8.73	59	1c	1	1c+1	
"	18306	168	46	1c	1	1	
"	18607	235^{UB}	-	-	-	-	
"	18613	206^{UB}	-	-	-	-	
18000 ± 3500	11913	210^{UB}	-	-	-	-	
18000 ± 3000	17308	200^{UB}	-	-	-	-	

UB = Unbroken

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 8

FATIGUE TEST RESULTS - NOTCH K_t = 3.4 2L65

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 11000	20205	0.422	42	7	39	12	0.061
"	20216	0.387	51	6	18	10	
"	21902	0.509	44	9	37	5	
18000 ± 10000	21501	0.466	41	18	25	1c+14	0.088
"	21502	0.450	43	1c+20	43	1c+18	
"	21505	0.386	68	1c+13	25	14	
"	21506	0.531	42	1c+14	34	10	
"	21510	0.466	50	12	40	18	
"	21515	0.443	45	4	32	6	
"	21519	0.465	56	15	49	1c+23	
"	21901	0.678	70	2c+11	47	8	
"	21905	0.567	46	8	36	8	
"	21910	0.668	51	4	42	4	
"	21915	0.662	43	1c+5	32	9	
"	21919	0.696	67	5	54	8	
18000 ± 9000	20201	0.925	56	1c+1	4	5	0.187
"	20214	0.569	54	11	39	8	
"	21818	1.41	55	1	24	2	
"	21906	1.41	46	1c	7	5	
18000 ± 8000	20219	1.31	49	2c	5	1c+1	0.170
"	21513	0.749	45	1	13	1c+2	
"	21918	1.62	44	1c	32	1c	
18000 ± 7500	20901	1.47	62	2	20	1c+2	0.147
"	20905	2.18	50	1c	26	1c+2	
"	20910	1.30	42	3	32	1	
"	20915	1.10	39	1	33	2	
"	20919	2.00	41	1c	2	6	
"	21401	3.23	52	1c	1	2	
"	21405	2.97	50	1c	3	3	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 8 (concluded)

Average stress on net area$_2$ lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 7500	21410	3.95	49	1c	3	1	
"	21415	1.88	51	1c	1	1c	
"	21419	2.19	53	1c	6	4	
"	21802	1.71	53	2	0	0	
"	21805	4.36	54	1c	2	2	
"	21810	2.21	49	1c	1	1c+1	
"	21815	1.63	44	1c	1	1c+4	
"	21819	2.03	47	2c	2	2	
18000 ± 7000	20202	0.931	52	3	8	1c	0.451
"	20215	1.44	51	1	3	3	
"	20902	4.85	59	1c	2	10	
"	20906	2.19	48	1c	3	1c+3	
"	21913	12.8	48	1c	1	2	
18000 ± 6000	20203	3.03	58	2c	0	0	0.360**
"	20211	8.63	52	4	1	1c+2	
"	20218	212^{UB}	-	-	-	-	
"	20913	2.39	41	1c	16	1c	
"	20918	3.56	50	1c	2	1c+4	
"	21518	2.77	50	1c	27	1c	
"	21813	12.4	52	2	1	1c	
18000 ± 5000	20206	4.40	49	1c	1	1	-
"	20212	71.7	51	4	1	2	
"	20213	94.4	57	6	14	5	
"	20217	260^{UB}	-	-	-	-	
"	21418	252^{UB}	-	-	-	-	
18000 ± 4000	20204	82.2^{UB}	-	-	-	-	-

UB = Unbroken

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

**Standard deviation calculated using J.S. Lariviere's method[12].

Table 9

FATIGUE TEST RESULTS - NOTCH K_t = 3.4 2024-TSI

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 12000	30612	0.269	46	15	19	1c+15	0.072
"	30613	0.262	48	12	38	13	
"	31118	0.353	39	1c+2	22	1c+6	
18000 ± 11000	30614	0.374	52	12	25	8	-
"	30615	0.360	43	15	11	3	
18000 ± 10000	30605	1.08	41	1c	37	1c+1	0.126
"	31101	0.655	46	1c+4	27	1c+2	
"	31105	0.836	56	6	15	1c+4	
"	31109	1.46	46	1	2	3	
"	31115	1.03	46	1c	6	1c	
"	31119	0.607	57	2c+4	56	1c+10	
"	31301	0.686	74	6	57	1c+5	
"	31305	0.817	50	4	40	2c+5	
"	31313	0.659	49	7	19	6	
"	31315	1.06	53	2	1	8	
"	31319	0.606	54	8	35	1c+4	
18000 ± 9000	30601	0.988	68	1c+4	0	0	0.027
"	30616	0.908	37	1c+1	34	1c	
"	30617	0.877	79	1	2	1	
18000 ± 8500	31602	2.19	46	1c	1	4	0.202
"	31605	2.27	43	1c	1	6	
"	31610	1.29	42	1c	4	3	
"	31615	1.48	47	1c	3	1c+5	
"	31619	1.50	45	1c	2	1c+4	
"	31701	2.52	52	1c	3	7	
"	31705	0.901	50	1	26	1c	
"	31710	3.59	50	1c	1	3	
"	31715	1.33	48	1c	4	5	
"	31719	0.824	49	1c	0	1	

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 9 (concluded)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
18000 ± 8000	30604	1.33	79	1	2	1c+1	0.123
"	30618	2.58	48	1c	2	2	
"	30619	1.55	45	1c	31	1c	
"	31613	1.76	40	1c	1	3	
18000 ± 7500	30606	18.1	46	1	0	0	0.759**
"	30607	2.13	62	1	0	0	
"	31302	1.84	46	1c	4	6	
"	31601	120^{UB}	-	-	-	-	
"	31606	29.7	50	1c	10	4	
"	31618	1.81	57	1	1	1	
18000 ± 7000	30602	27.6^{UB}	-	-	-	-	-
"	30603	44.4	49	1c	1	1c+9	

UB = Unbroken.

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

**Standard deviation calculated using J.S. Lariviere's method[12].

Table 10

FATIGUE TEST RESULTS - NOTCH K_t = 3.4 Al 6% Cu

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
13100 ± 10000	40404	1.55	61	2	14	1	0.153
"	40414	1.38	55	2	32	1c	
"	40511	0.879	70	1c+3	17	2	
"	40516	0.874	54	1c+2	35	1	
"	40601	0.658	58	5	52	3	
"	40603	0.933	56	1c+6	34	1c+1	
"	40616	1.30	63	1c+1	16	1	
"	40619	1.40	67	5	59	2c	
"	40706	1.02	70	2c+1	46	1c+2	
"	40710	1.56	61	2c	20	1	
"	40806	1.40	58	2c+1	58	2	
"	40811	0.900	54	2	40	3	
"	40907	1.37	69	1c+1	18	1c+3	
"	40913	1.51	60	1c+1	53	1c+2	
"	41002	0.846	66	1c+5	51	1c+3	
"	41003	0.653	47	1c+4	44	1c+3	
"	41116	0.480	47	5	44	3	
"	41119	0.870	61	2	41	2	
"	41202	0.656	54	1c+2	34	2	
13100 ± 7000	40518	2.30	73	2c	0	0	0.034
"	41117	2.69	85	1c	34	1	
"	41219	2.51	67	1c+1	64	1c+2	
13100 ± 5000	40501	10.2	86	1c	14	1	0.146
"	40617	6.26	86	1c	12	1	
"	41017	5.35	82	1c	34	1c	
13100 ± 4000	40402	8.90	90	1c	16	1	0.486
"	40417	14.2	86	1c	16	1	
"	40503	10.1	84	1c	39	1c+1	
"	41118	98.3	86	1c	18	1	
13100 ± 3000	40502	1010^{UB}	-	-	-	-	-
"	41004	16.0	88	1c	17	1	

UB = Unbroken.

* e.g. 2c+3 means that there were 5 nuclei, one at each corner of the hole and three along the bore.

Table 11

FATIGUE TEST RESULTS - LUG SPECIMEN DTD 5014

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
15000 ± 6150	50501	0.967	86	6	62	7	0.083
"	50505	0.765	78	8	44	6	
"	50510	0.871	74	1c+7	74	1c+7	
"	50515	0.796	83	2c+5	65	1c+5	
"	50519	0.804	78	1c+5	71	3	
"	52001	0.564	79	16	60	10	
"	52005	0.580	80	1c+6	58	9	
"	52010	0.509	73	1c+7	41	6	
"	52015	0.599	76	1c+6	54	1c+6	
"	52019	0.638	79	8	57	7	
"	53101	0.811	73	6	63	6	
"	53105	0.727	80	12	55	1c+6	
"	53110	0.754	82	8	59	1c+9	
"	53115	0.673	80	8	62	9	
"	53119	0.779	76	1c+4	45	2	
"	53803	0.817	78	6	53	7	
"	53815	0.561	70	16	64	1c+14	
"	58401	0.624	80	7	70	2	
"	58405	0.554	77	10	66	1c+8	
"	58410	0.532	82	1c+9	62	11	
"	58415	0.556	78	6	70	5	
"	58419	0.516	76	6	70	12	
15000 ± 5110	53804	1.02	79	1c+5	53	2c+4	
"	53817	0.943	74	1c+6	68	5	
15000 ± 5000	50402	1.14	83	3	54	1c+7	0.029
"	50411	0.980	76	1c+6	67	1c+6	
"	50416	1.08	78	5	75	5	
"	53102	1.12	70	1c+3	68	1c+7	
15000 ± 4090	53805	2.88	78	4	62	1c+1	
"	53818	9.54	80	1c+5	60	2c	
15000 ± 4000	50403	2.37	80	4	62	4	0.066
"	50418	1.71	78	1c+1	65	6	
"	53107	1.92	75	2	68	1c+4	
"	53113	1.72	82	1c+2	34	1c+1	

* e.g. 2c+1 means that there were three nuclei, one at each corner of the hole and one along the bore.

Table 11 (continued)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
15000 ± 3075	53801	9.06	84	1	21	2	
15000 ± 3000	50405	4.86	79	3	44	2	0.071
"	50409	4.52	78	3	69	2	
"	50412	3.86	79	2	42	1c+1	
"	50507	3.45	76	1	68	2	
"	51513	5.10	81	2	58	2	
15000 ± 2045	50518	20.0	82	1	58	1c	0.157
"	51502	21.6	81	1c	32	1c+1	
"	51505	23.3	83	4	44	1c+3	
"	51510	19.4	79	4	53	4	
"	51515	18.7	85	2	5	1c	
"	51518	20.2	85	2	25	5	
"	52901	16.3	83	1c+1	38	1c+1	
"	52905	14.8	82	1c	36	1	
"	52910	11.1	79	1	17	1c+3	
"	52915	24.6	86	1c+1	49	1c+1	
"	52919	25.0	77	1c+1	34	1c+2	
"	53807	49.1	87	2	49	2	
"	53808	31.1	82	1c+2	18	1c+2	
"	53816	24.3	74	1c	39	1c	
"	55201	16.7	80	1c	55	1	
"	55205	16.5	81	1	33	1c+2	
"	55210	13.5	76	1c	25	1c+6	
"	55215	11.8	76	1c	35	1c	
"	55219	15.1	81	1	48	1	
"	55601	12.4	79	1c+5	16	1c+1	
"	55605	7.67	83	1	1	3	
"	55610	14.5	80	1c+2	67	7	
"	55615	14.4	80	1c+2	40	3	
"	55619	15.9	82	1c+1	45	6	
"	58101	11.2	83	1	34	2c	
"	58105	15.4	76	2	33	1c+2	
"	58110	16.2	76	1c+1	65	2	
"	58115	14.4	73	1	40	1	
"	58119	12.1	80	1c+1	10	1c	

* e.g. 2c+1 means that there were three nuclei, one at each corner of the hole and one along the bore.

Table 11 (concluded)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
15000 ± 2000	51819	16.6	83	1c+3	20	1	
15000 ± 1708	53806	38.9	84	1c+1	5	1c	
15000 ± 1500	50406	64.4	84	1c+1	5	1c+2	0.128
"	50408	31.1	84	1c+1	8	1c	
"	50414	30.0	83	1	1	4	
"	50513	31.2	79	1	68	2	
"	51507	36.4	85	1c	4	1c+1	
"	52902	31.2	83.	2	1	2c	

* e.g. 2c+1 means that there were three nuclei, one at each corner of the hole and one along the bore.

Table 12

FATIGUE TEST RESULTS - LUG SPECIMEN 2L65

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
15000 ± 9000	61216	0.422	90	1c+6	67	1c+6	-
15000 ± 8000	61217	0.422	82	7	56	8	0.113
"	61602	0.439	80	1c+7	50	10	
"	61606	0.275	80	3	33	11	
15000 ± 7000	61218	0.668	78	1c+4	65	1c+9	-
15000 ± 6000	61213	0.810	78	6	67	6	0.070
"	61601	0.757	82	12	63	6	
"	61605	0.484	80	1c+1	46	1c+1	
"	61610	0.618	80	6	65	7	
"	61615	0.583	78	1c+5	71	1c+4	
"	61619	0.636	86	4	18	1c+1	
15000 ± 5000	61219	1.05	84	6	71	5	-
15000 ± 4000	61214	3.09	80	1	63	1	-
"	61618	1.43	81	1c	58	2	
15000 ± 3500	60401	3.56	83	4	40	4	0.128
"	60402	3.27	84	1c+1	38	5	
"	60405	4.41	83	2	3	3	
"	60410	4.10	80	5	50	3	
"	60415	2.10	82	3	3	2	
"	60419	2.47	80	3	50	3	
"	61301	2.67	84	1c	28	1	
"	61305	2.61	79	1c	61	1c+1	
"	61310	1.94	83	1c	60	1c	
"	61315	1.96	82	1c+2	38	1c+2	
"	61319	2.48	83	1c	39	2c+1	
15000 ± 2500	61215	25.8	83	3	29	3	-
"	61613	6.67	82	1c	63	1c+1	

* e.g. 2c+1 means that there were three nuclei, one at each corner of the hole and one along the bore.

Table 12 (concluded)

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
15000 ±2000	60413	19.0	80	3	63	3	0.044
"	60418	17.2	84	1	42	1	
"	61207	21.8	83	4	37	5	
"	61210	20.2	84	1c+3	1	1	
15000 ± 1500	61307	25.9	83	1c	48	1c+1	0.101
"	61313	34.6	83	1c	52	1c	
"	61318	21.8	82	5	10	1	

* e.g. 2c+1 means that there were three nuclei, one at each corner of the hole and one along the bore.

Table 13

FATIGUE TEST RESULTS - LUG SPECIMEN 2024-T81

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
15000 ± 9000	70716	0.307	80	1c+4	68	10	-
15000 ± 8000	70216	0.420	89	6	60	1c+4	-
"	70217	0.423	78	3	48	2c+7	
15000 ± 7000	70215	0.620	79	2	65	4	-
15000 ± 6000	70713	0.698	83	1c	17	1c+5	0.076
"	71201	0.663	77	3	53	1c+2	
"	71205	0.744	83	7	60	1c+3	
"	71210	0.651	82	1c+5	56	1c+6	
"	71213	0.636	86	1c+1	75	7	
"	71219	0.597	80	5	67	1c+5	
15000 ± 5000	70214	0.864	87	1c+2	32	1c+5	-
"	70218	0.870	80	1c+1	75	1c+6	
15000 ± 4000	70714	1.46	78	1c	39	2c+1	-
"	71218	1.56	78	1c	60	4	
15000 ± 3500	70701	2.56	81	1c	46	2c+2	0.077
"	70705	3.32	84	1c	8	1c	
"	70710	2.77	82	1c	8	2c+1	
"	70717	2.31	82	1c	13	1c+3	
"	70719	3.53	81	1c	14	2c+2	
15000 ± 3000	70213	5.61	83	1c	19	2c+1	-
"	70219	7.28	87	3	30	3	
15000 ± 2000	70715	12.9	85	1c+1	70	1c+1	0.141
"	71202	22.0	83	1c+1	68	1c+2	
"	71206	12.2	84	1	78	2	

* e.g. 2c+1 means that there were three nuclei, one at each corner of the hole and one along the bore.

Table 14

FATIGUE TEST RESULTS - LUG SPECIMEN Al 6% Cu

Average stress on net area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Major fatigue crack		Minor fatigue crack		Estimated standard deviation of $\log_{10}N$
			Area on half the net section %	Number* of damage nuclei	Area on half the net section %	Number* of damage nuclei	
12000 ± 9000	80610	0.471	-	-	-	-	-
12000 ± 7000	80103	1.19	81	2c+2	61	1c+1	0.045
"	80105	1.06	83	1	57	2c	
"	80119	0.924	69	1c+1	47	1c+1	
"	80403	1.12	74	1c	67	1c+3	
"	80502	1.17	73	1c+2	53	1c+1	
"	80514	1.12	73	1c+2	68	1c	
"	80604	0.953	69	2c+2	62	1c+2	
"	80611	0.938	69	2	56	1	
12000 ± 3100	80117	5.73	84	1c	41	1c	-
"	80405	8.17	88	1c	78	3	
12000 ± 3000	80613	3.88	89	1c	40	1c	-
12000 ± 2000	80118	24.1	88	1c	40	1c+1	0.076
"	80314	23.7	90	1c	43	1c	
"	80402	18.4	89	1c	22	1c	
"	80416	19.2	89	1c	44	1	
"	80509	17.3	-	-	-	-	
"	80512	21.0	85	1c	65	1c	
"	80603	15.9	88	1c	0	0	
"	80606	14.9	88	1c	38	1c	
12000 ± 1300	80205	42.4	83	1	61	1	-
"	80414	40.9	85	1c	0	0	
12000 ± 700	80419	234$^{\mathrm{UB}}$	-	-	-	-	-

UB = Unbroken.

* e.g. 2c+1 means that there were three nuclei, one at each corner of the hole and one along the bore.

Table 15

FATIGUE TEST RESULTS - JOINT SPECIMEN DTD 5014

Average stress on gross area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Estimated standard deviation of $\log_{10}N$
15000 ± 12080	51101	1.63	0.278
"	51105	1.22	
"	51110	0.899	
"	51115	1.56	
"	53401	1.78	
"	53405	6.01	
"	53410	6.36	
"	53415	2.94	
"	53418	1.10	
"	53507	1.11	
"	53512	1.45	
"	53513	1.50	
15000 ± 10000	53502	3.13	-
15000 ± 8960	51102	2.86	0.100
"	51113	2.86	
"	52509	2.92	
"	54002	3.04	
"	54006	2.66	
"	54010	2.95	
"	54015	1.92	
"	54019	3.00	
"	54501	2.97	
"	54505	2.82	
"	54510	3.76	
"	54515	4.64	
"	54519	3.45	
"	54902	4.11	
"	54905	3.55	
"	54910	3.61	
"	54915	4.41	
"	54919	3.07	
"	59301	3.24	
"	59307	2.47	
"	59310	2.48	
"	59315	3.24	
"	59319	1.74	

Table 15 (concluded)

Average stress on gross area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Estimated standard deviation of $\log_{10}N$
15000 ± 7920	53503	4.59	-
15000 ± 7000	50907	5.24	0.161
"	53417	4.30	
"	54407	5.29	
15000 ± 6040	53504	9.01	-
15000 ± 6000	54018	6.06	-
15000 ± 5000	53509	13.6	-
"	54513	8.77	
15000 ± 4580	53514	13.6	-
"	53515	13.6	-
15000 ± 4190	50902	20.0	0.164
"	50905	11.4	
"	50910	16.7	
"	50915	14.4	
"	50919	17.7	
"	51401	9.62	
"	51405	21.6	
"	51410	17.0	
"	51415	22.3	
"	51419	13.3	
"	52501	10.1	
"	52505	8.87	
"	52510	10.2	
"	52515	11.9	
"	52519	8.00	
"	53518	23.0	
"	53519	21.2	
"	54401	32.1	
"	54405	9.60	
"	54410	16.0	
"	54415	20.7	
"	54419	19.6	
15000 ± 3960	53506	37.0	-
15000 ± 3000	51407	42.8	-
"	54013	78.5	
15000 ± 2920	53510	120	-

Table 16

FATIGUE TEST RESULTS - JOINT SPECIMEN 2L65

Average stress on gross area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Estimated standard deviation of $\log_{10}N$
15000 ± 11000	61205	2.90	-
15000 ± 10000	60501	3.38	0.142
"	60602	1.95	
"	60607	2.28	
"	60610	1.29	
"	60615	2.26	
"	60619	2.76	
15000 ± 9000	61201	2.45	-
15000 ± 7000	61204	5.60	-
15000 ± 6000	61206	6.67	-
15000 ± 5000	60502	8.80	0.065
"	60505	8.12	
"	60510	8.47	
"	60515	7.05	
"	60519	7.09	
"	60601	9.08	
"	60605	6.49	
"	61208	6.03	
15000 ± 3000	60513	39.1	-
"	60613	26.0	

Table 17

FATIGUE TEST RESULTS - JOINT SPECIMEN 2024-T81

Average stress on gross area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Estimated standard deviation of $\log_{10}N$
15000 ± 11000	70203	1.52	-
15000 ± 10000	70401	2.20	0.093
"	70405	1.97	
"	70410	2.15	
"	70415	2.38	
"	70419	1.38	
15000 ± 9000	70201	3.03	-
15000 ± 8000	70204	2.28	-
15000 ± 7000	70205	3.82	-
"	70513	4.98	
15000 ± 6000	70206	5.79	-
15000 ± 5000	70207	7.74	0.114
"	70501	7.79	
"	70505	8.21	
"	70510	7.47	
"	70515	7.45	
"	70519	4.16	
"	71001	8.53	
"	71005	8.92	
"	71010	10.6	
"	71015	11.9	
"	71019	7.91	
15000 ± 4000	70208	15.3	-
15000 ± 3000	70502	28.6	0.119
"	70506	19.4	
"	70518	33.0	
15000 ± 2000	71013	238^{UB}	-

UB = Unbroken

Table 18

FATIGUE TEST RESULTS - JOINT SPECIMEN Al 6% Cu

Average stress on gross area lb/in^2	Specimen No.	Endurance (N) 10^5 cycles	Estimated standard deviation of $\log_{10}N$
10980 ± 9760	80201	2.68	-
"	80216	1.80	
10980 ± 6710	80211	3.08	-
"	80213	4.89	
10980 ± 4270	80209	11.2	-
"	80217	17.5	
10980 ± 3050	80202	19.5	0.174
"	80203	27.5	
"	80309	45.9	
"	80311	35.4	
"	80409	52.1	
"	80413	37.5	
"	80504	15.9	
"	80505	44.5	
"	80506	23.8	
"	80511	27.7	
"	80518	18.5	

Table 19

TRANSITION STRESS FROM SINGLE TO MULTIPLE NUCLEI

Material	Mean UTS lb/in^2	Transition stress lb/in^2	
		2.3 notch	3.4 notch
DTD 5014	62830	18000 ± 13500	18000 ± 6700
2L65	72130	18000 ± 16000	18000 ± 8200
2024-T81	77530	18000 ± 16000	18000 ± 9000
Al 6% Cu	66390	18000 ± 13600	13100 ± 7900

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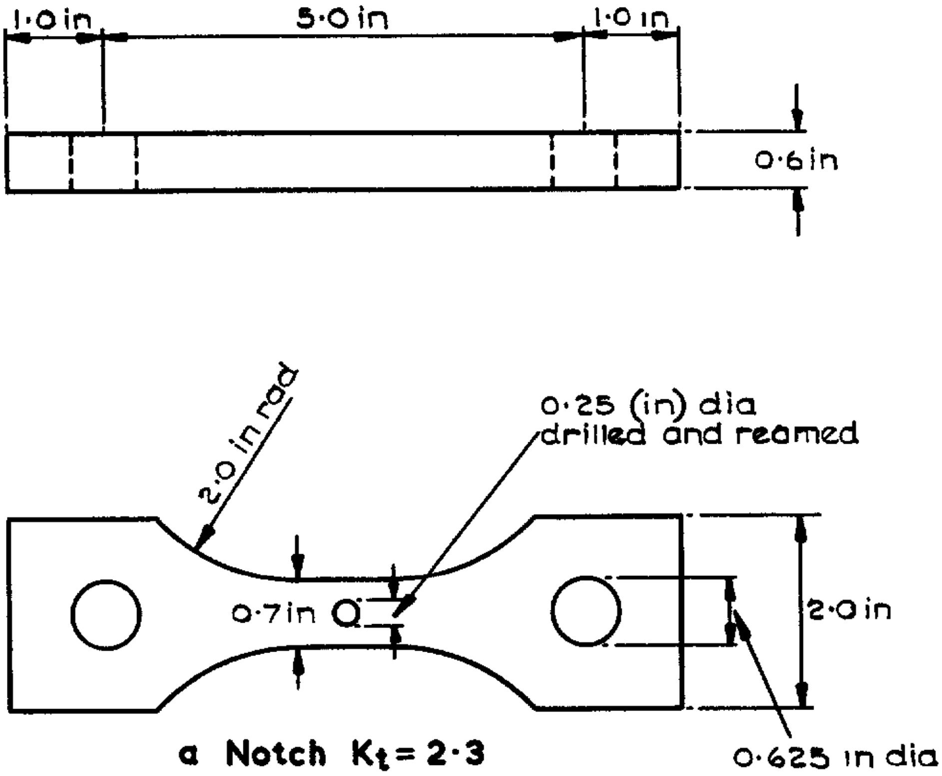
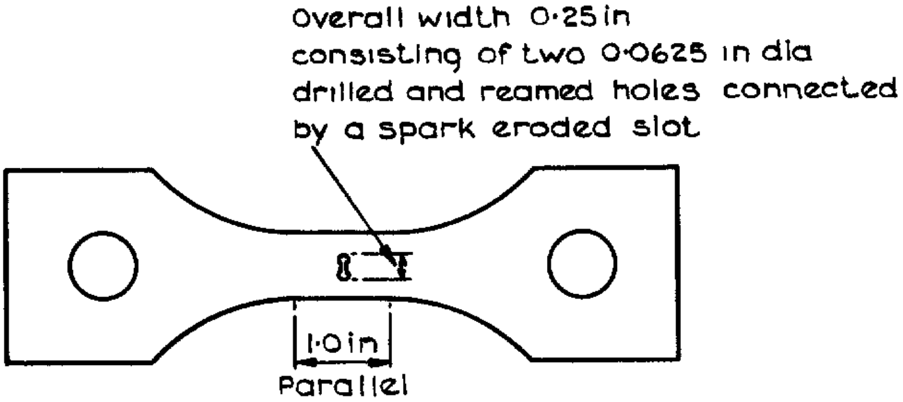


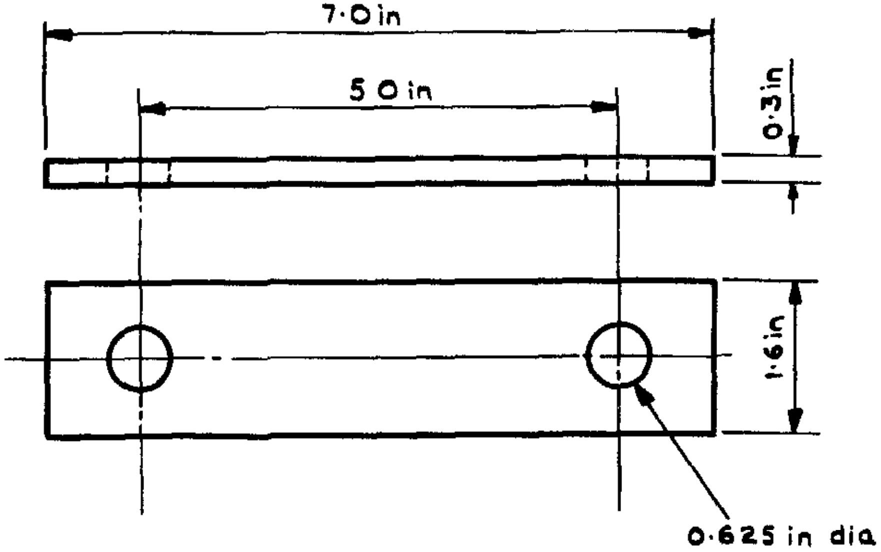
a Notch $K_t = 2\cdot3$



b Notch $K_t = 3\cdot4$

Surface finish:- 8 to 16 micro inches
Edges of holes at test section sharp and free from burrs

Fig. 1a&b Notched specimens



Surface finish:
8 to 16 micro-inches

Fig. 2 Lug specimen

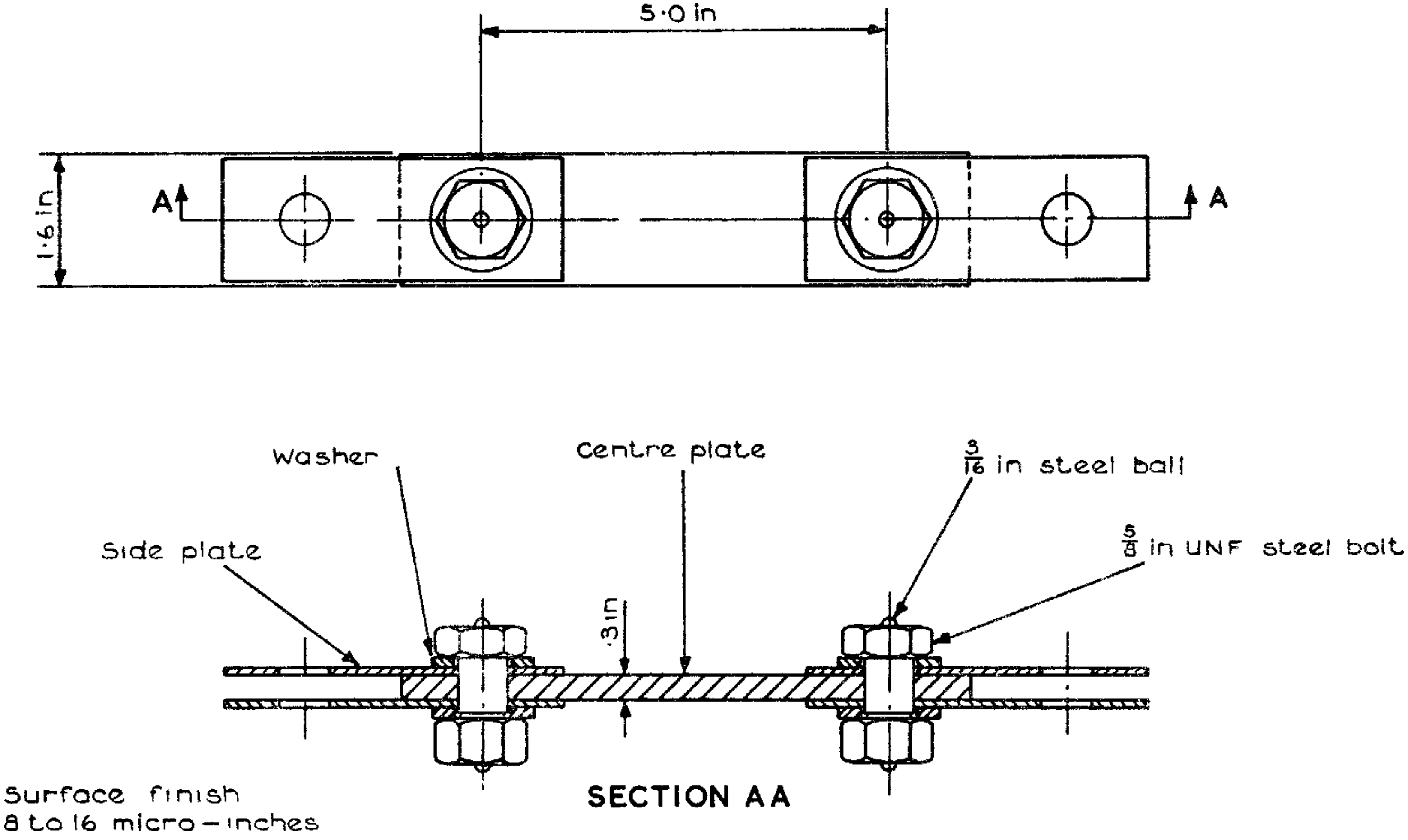
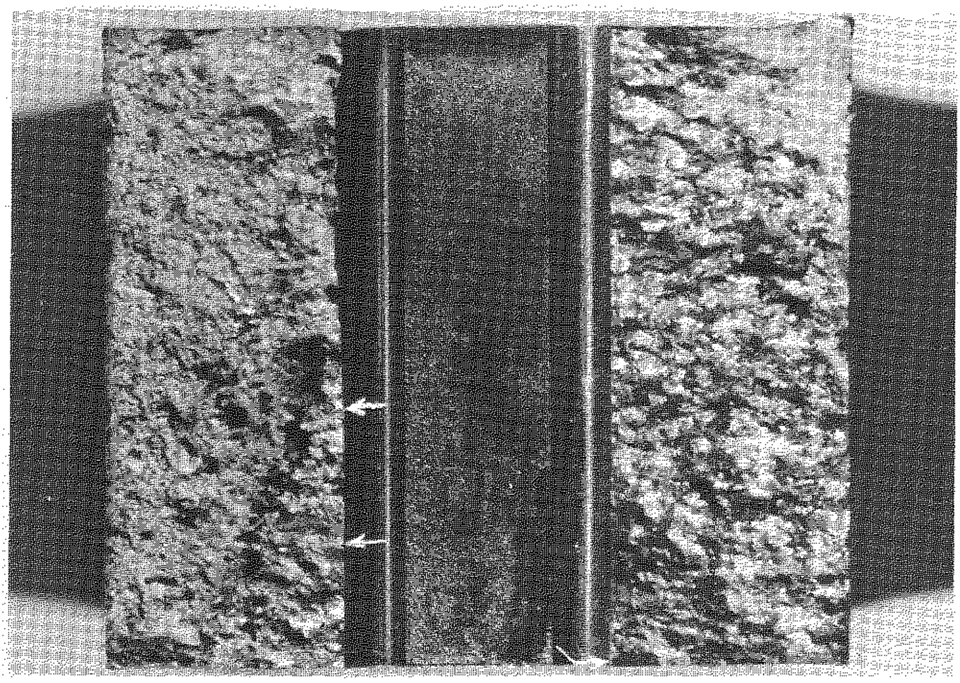
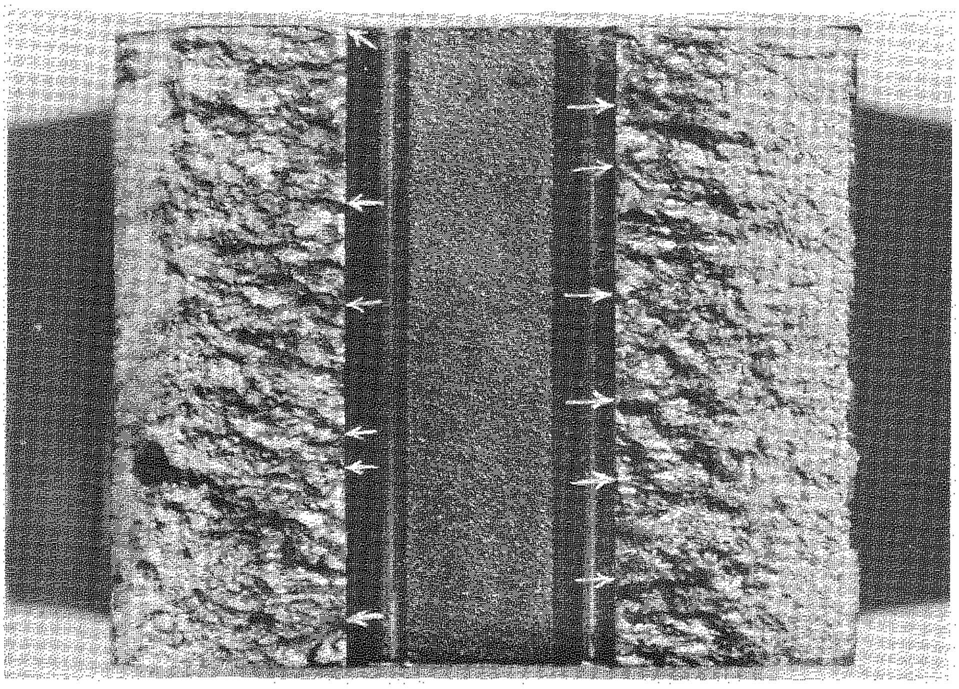


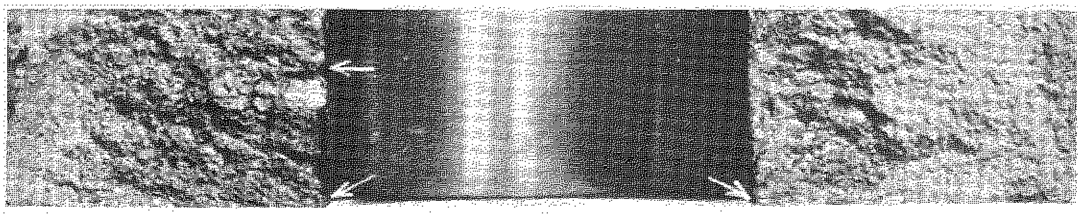
Fig. 3 Joint specimen



a. K_t=3.4—small number of damage nuclei

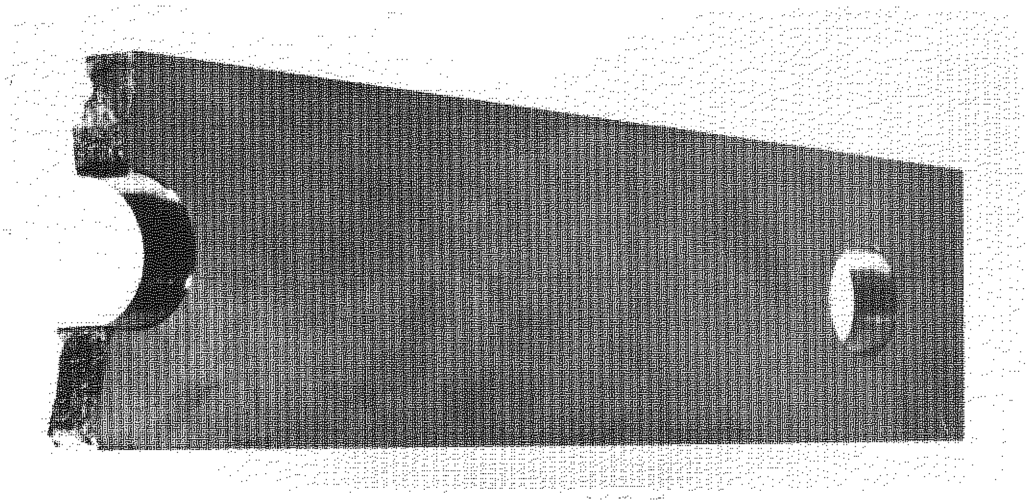


b. K_t=3.4 large number of damage nuclei

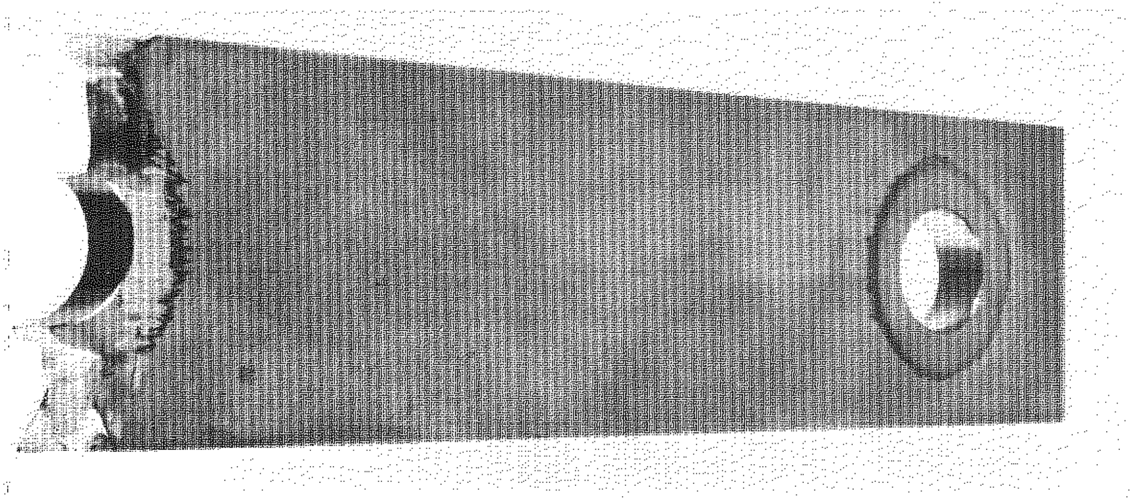


c. Lug

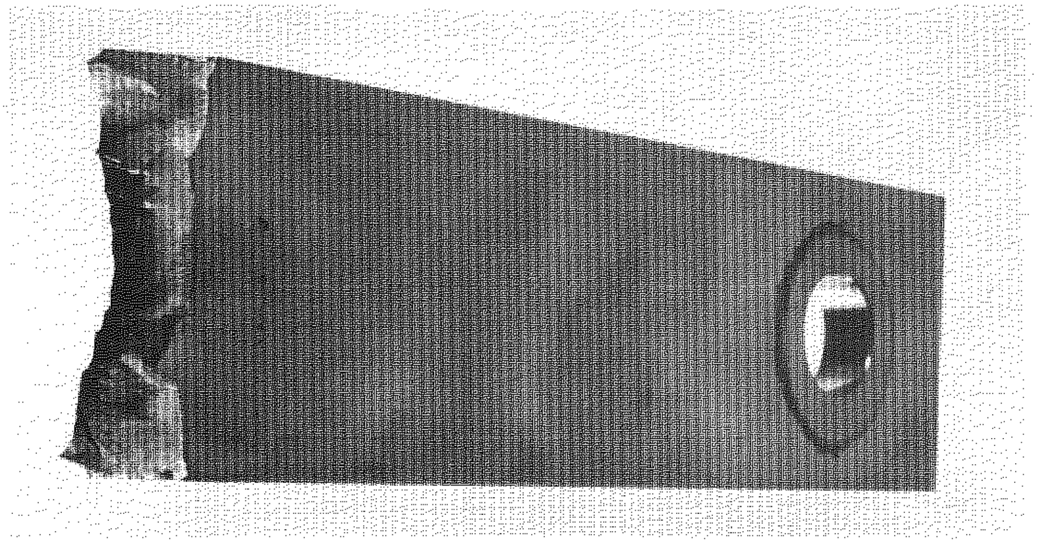
Fig.4. Appearance of fracture surfaces showing positions of damage nuclei



a. Lug



b. Joint (failure through hole)



c. Joint (failure away from hole)

Fig.5. Typical fractures on lug and joint specimens

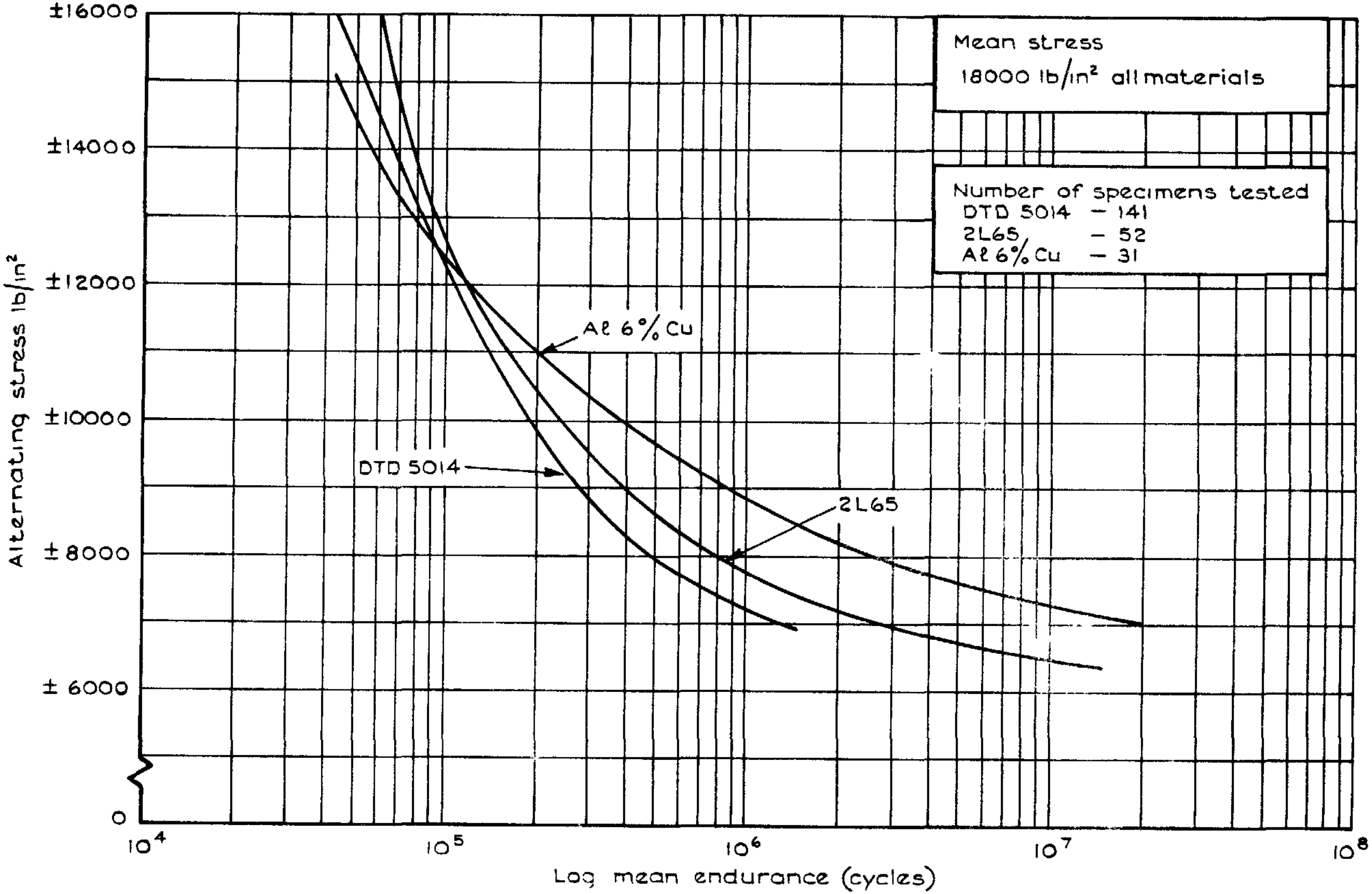


Fig 6 Variation of mean endurance with alternating stress for 2·3 notch in three materials

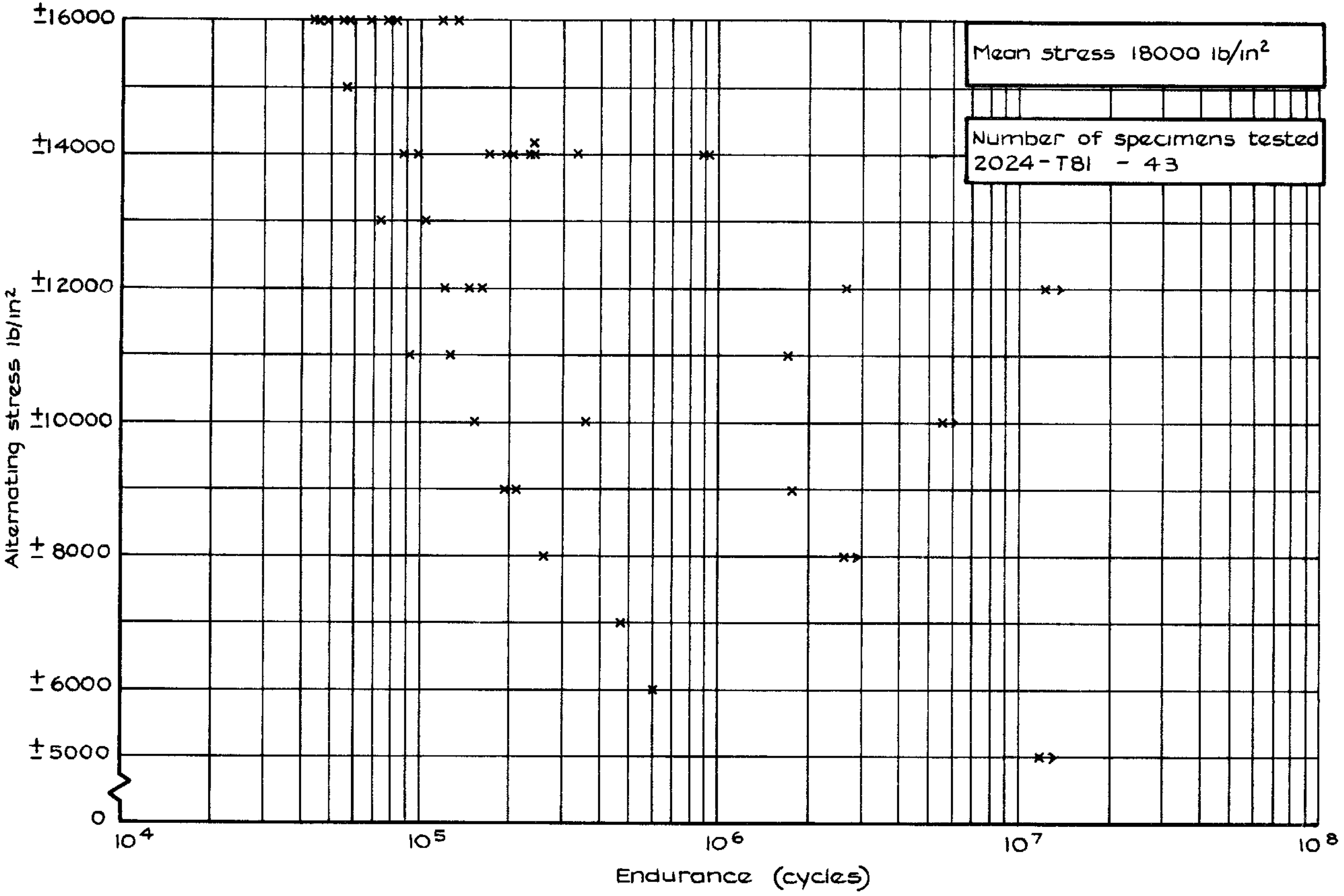


Fig. 7 Variation of endurance with alternating stress for 2·3 notch, 2024-T81 material

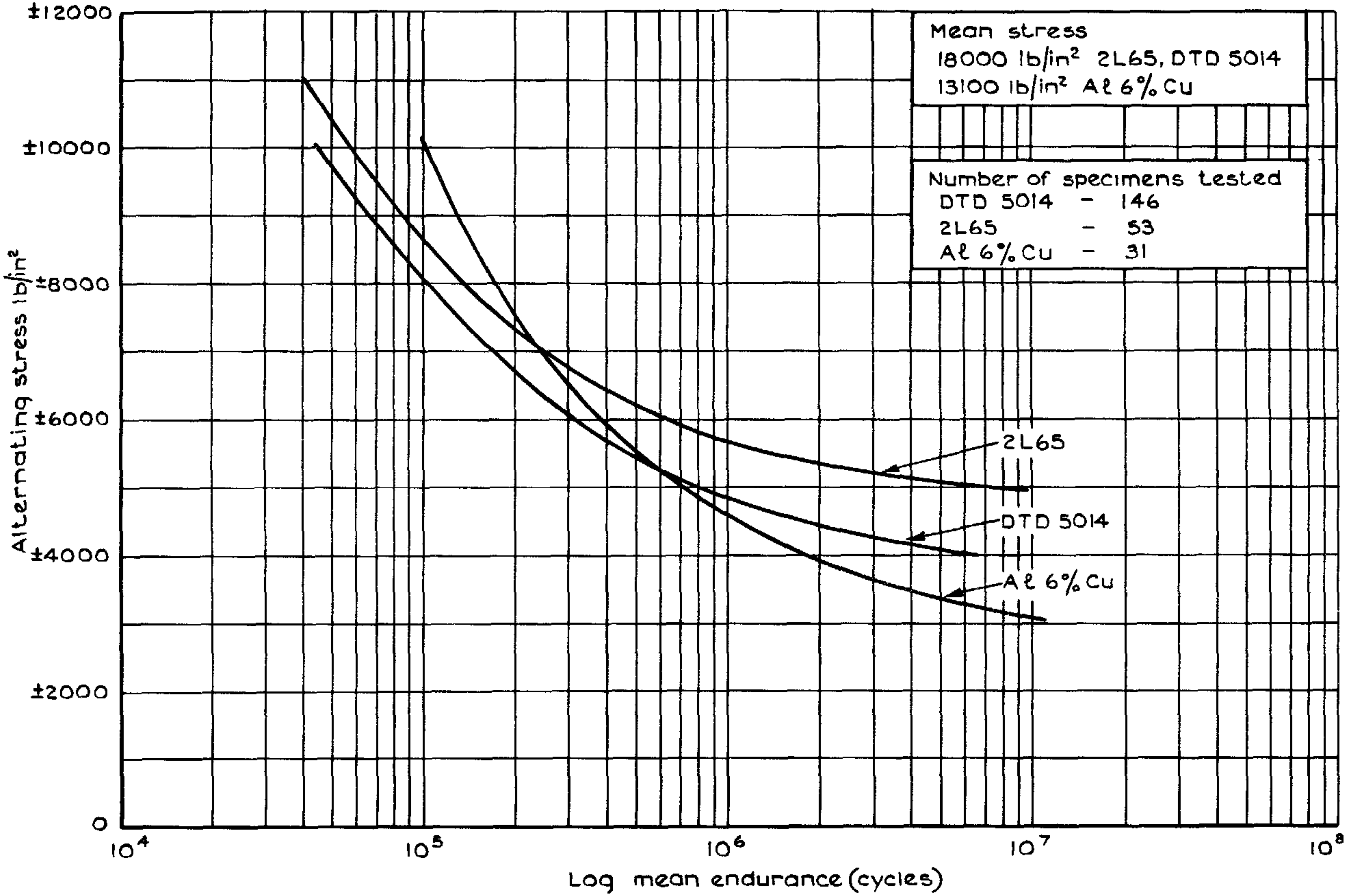


Fig. 8 Variation of mean endurance with alternating stress for 3·4 notch in three materials

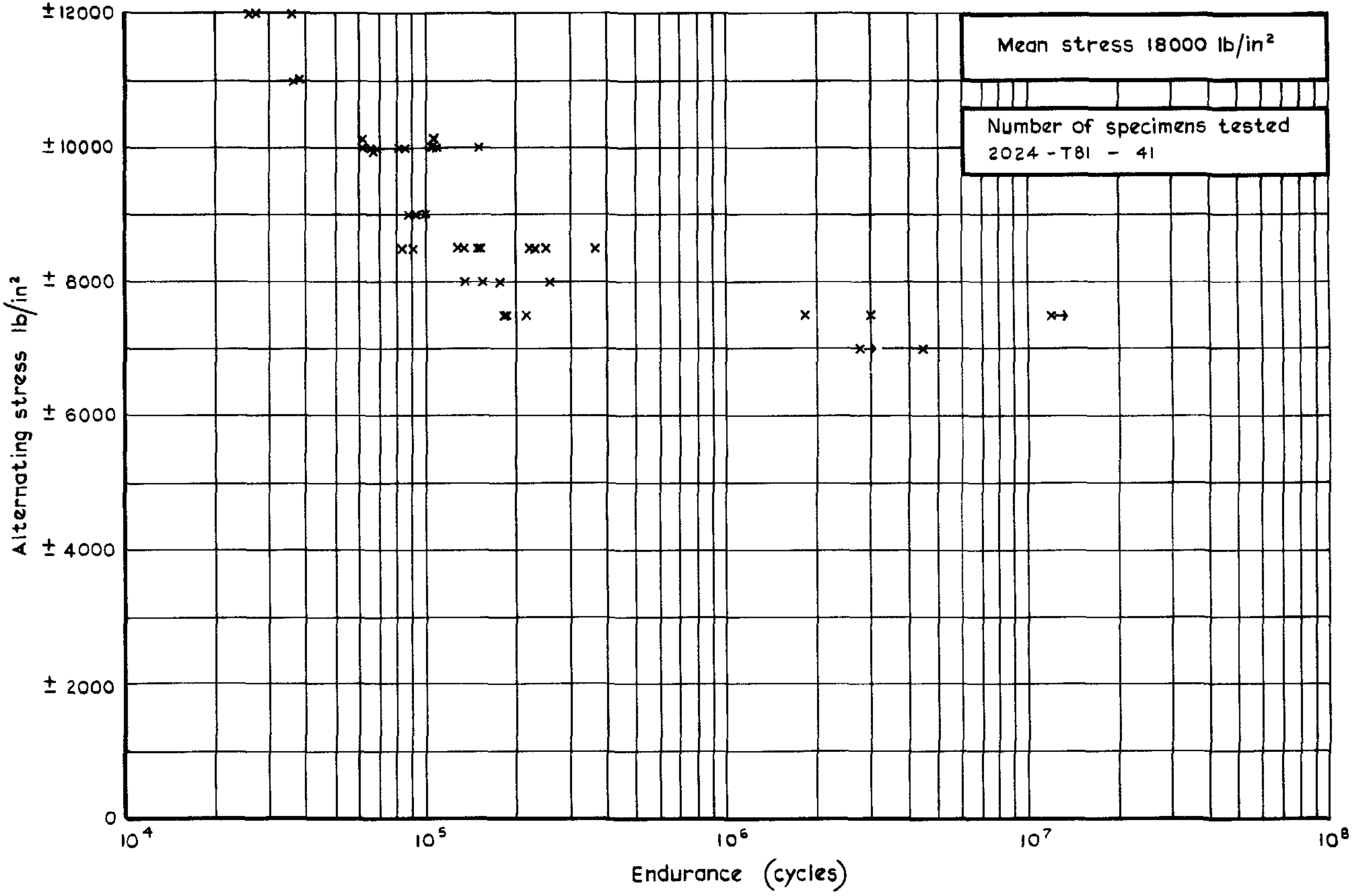


Fig.9 Variation of endurance with alternating stress for 3·4 notch, 2024-T81 material

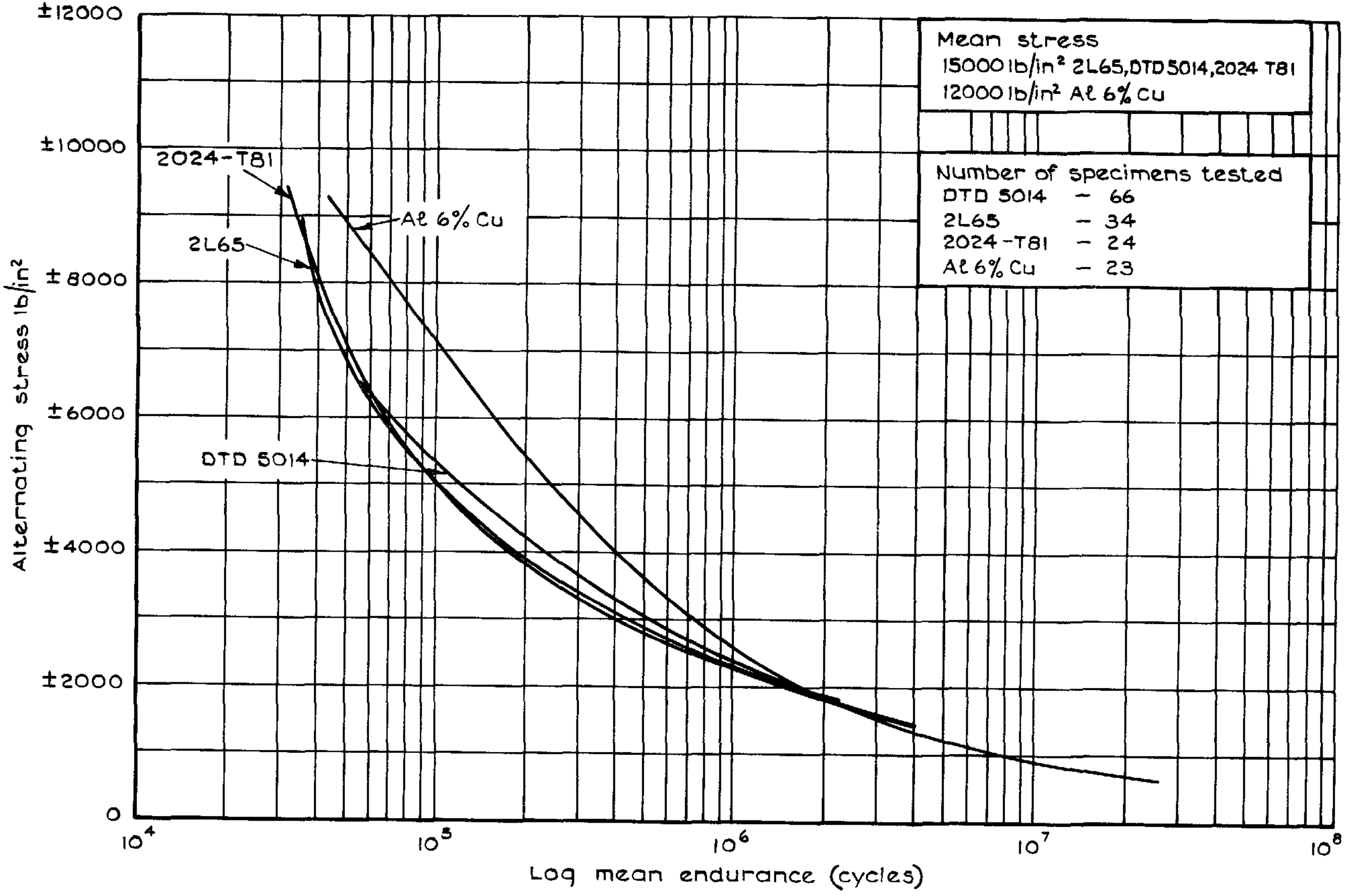


Fig. 10 Variation of mean endurance with alternating stress for lug specimen

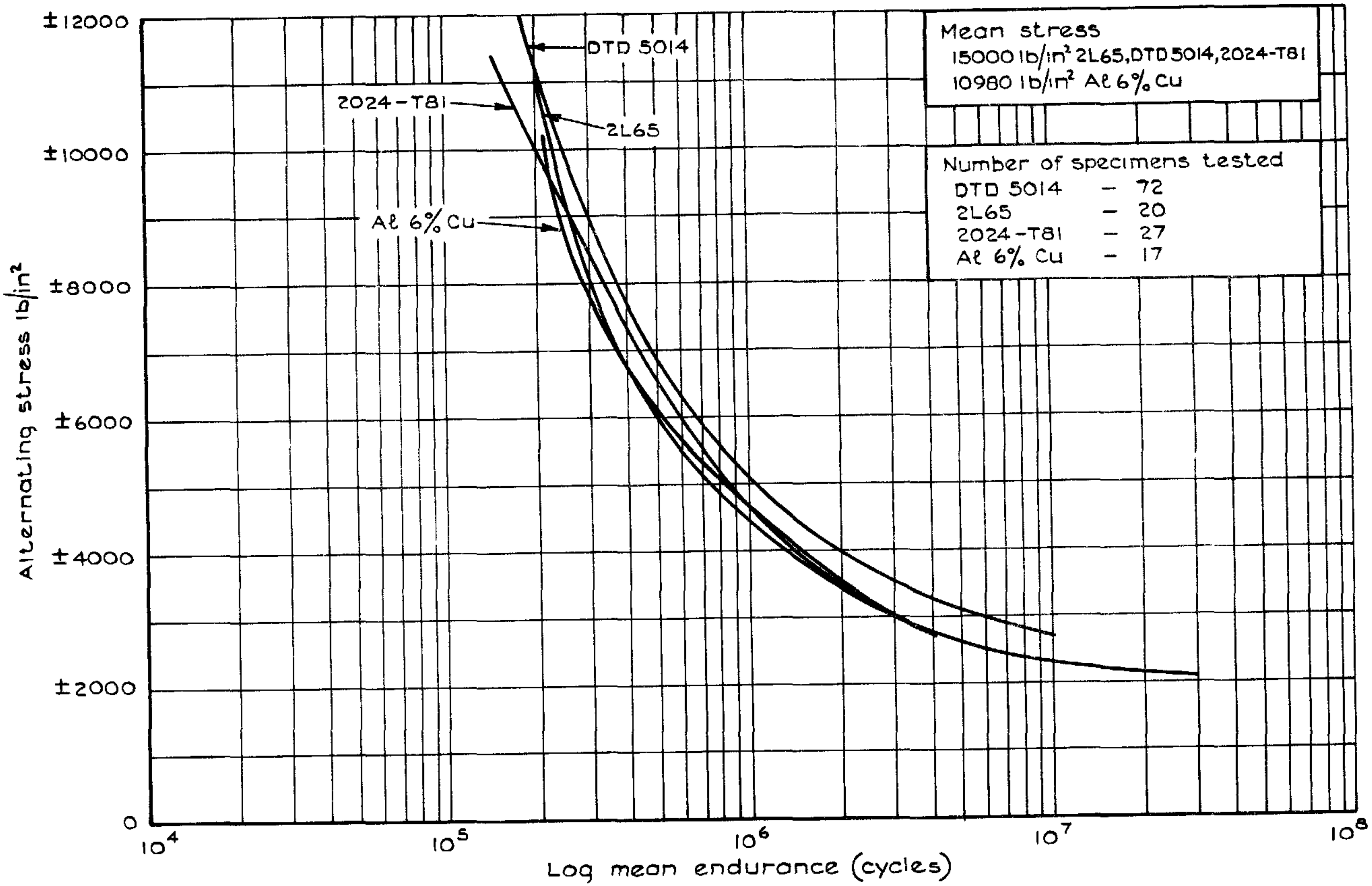


Fig.11 Variation of mean endurance with alternating stress for joint specimen

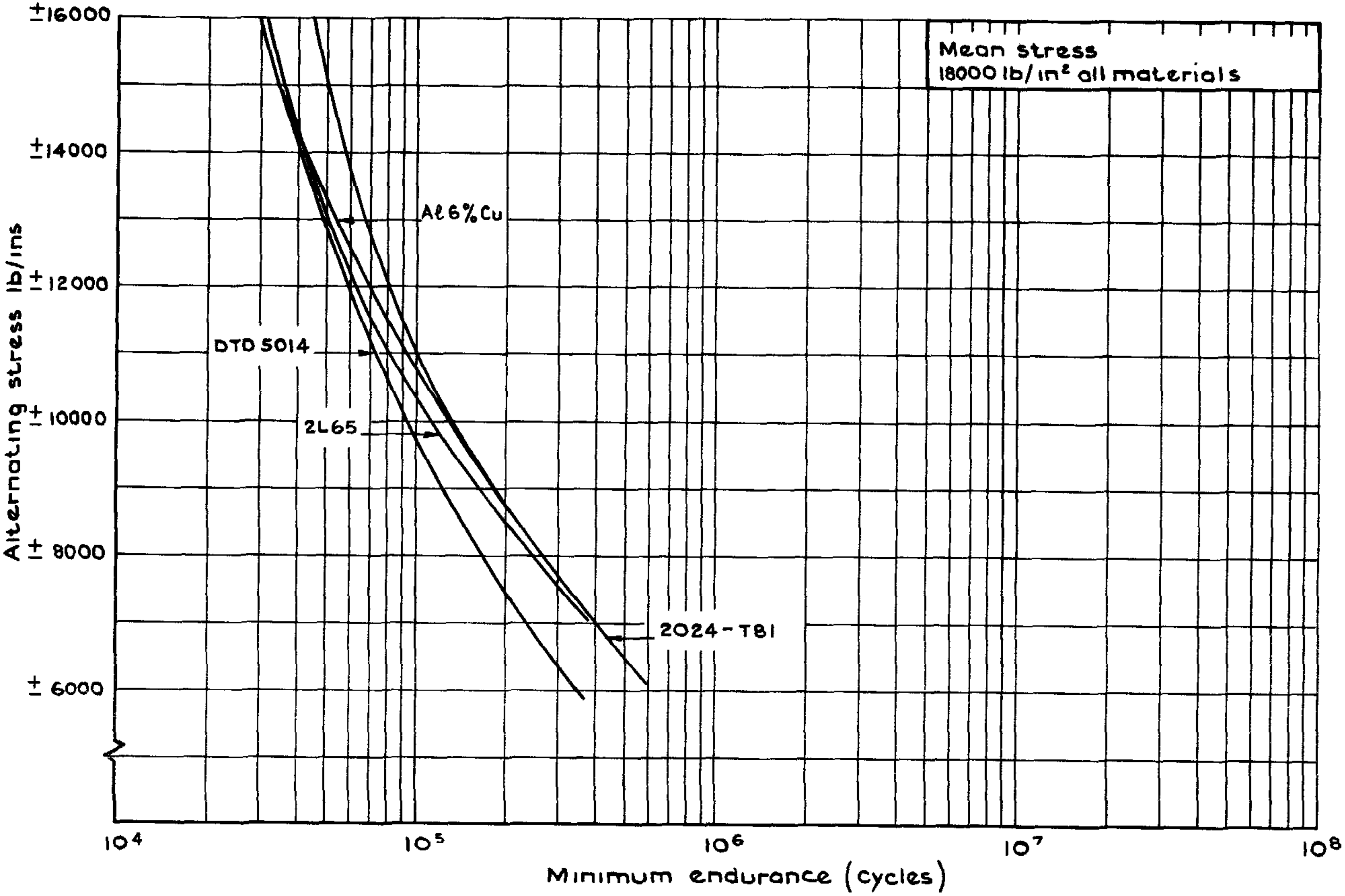


Fig.12 Variation of minimum endurance with alternating stress for 2·3 notch

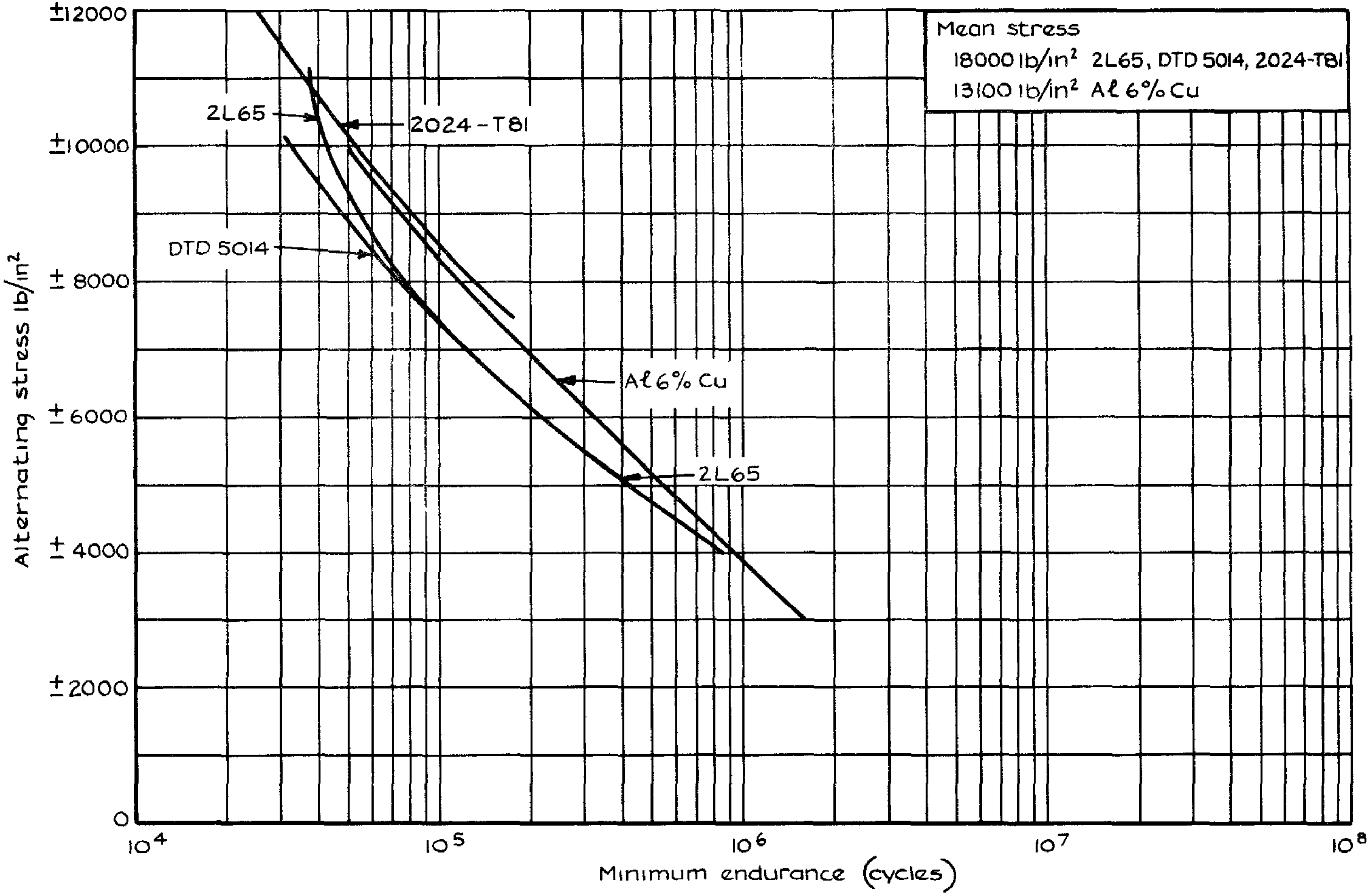


Fig. 13 Variation of minimum endurance with alternating stress for 3·4 notch

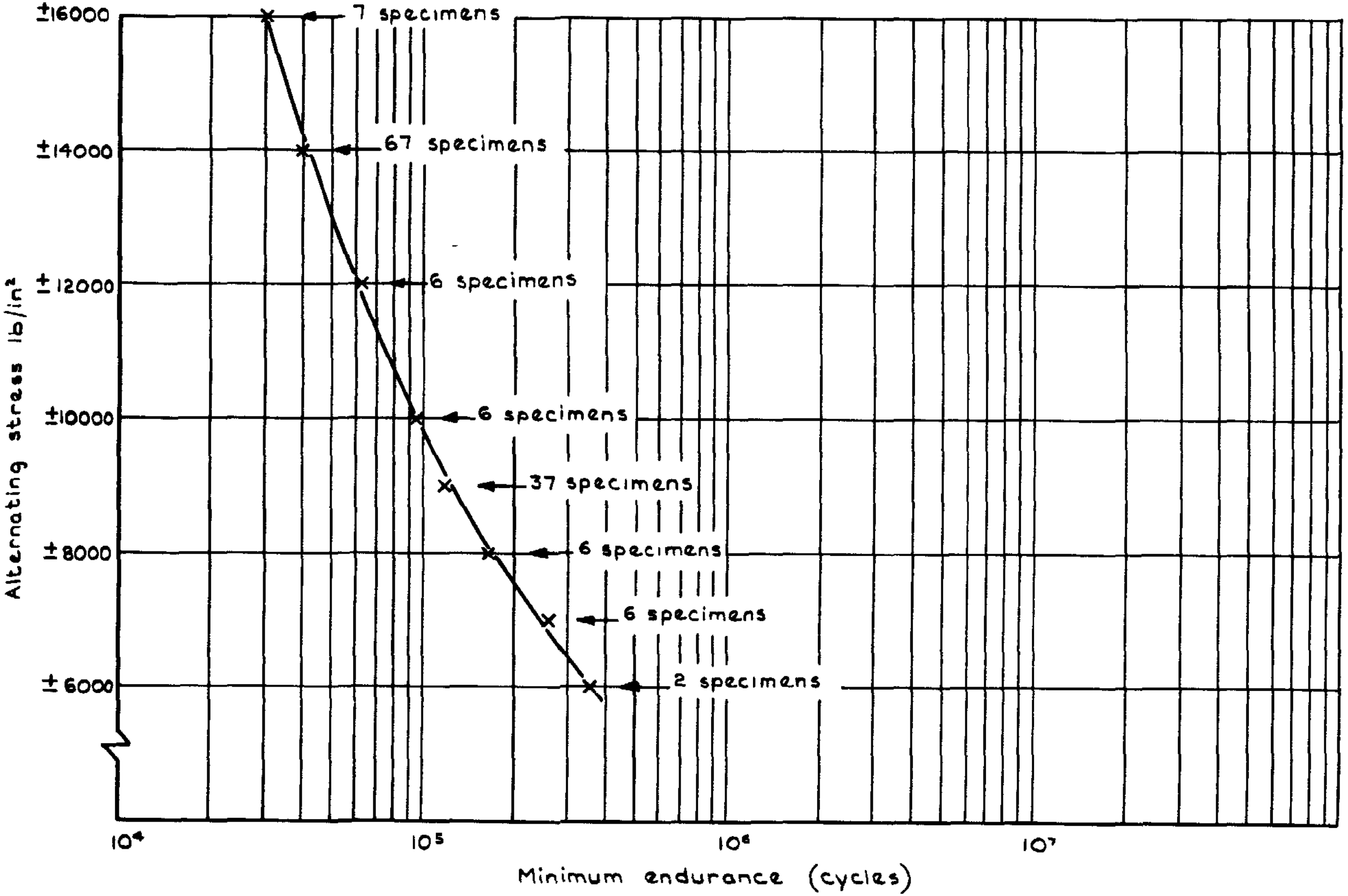


Fig.14 Variation of minimum endurance with alternating stress for the 2·3 notch in DTD 5014 material

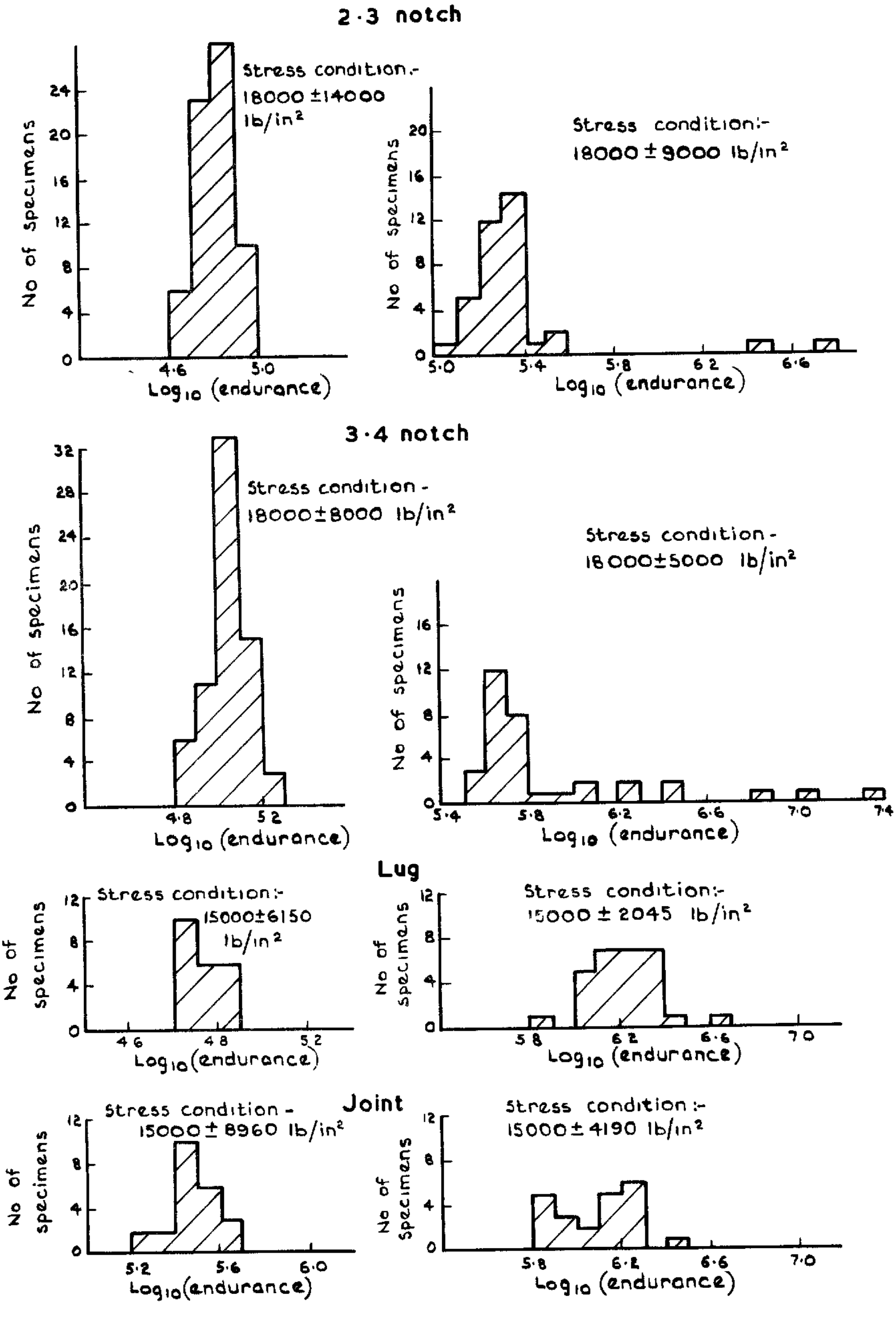


Fig. 15 Distribution of endurances of specimens in DTD 5014 material

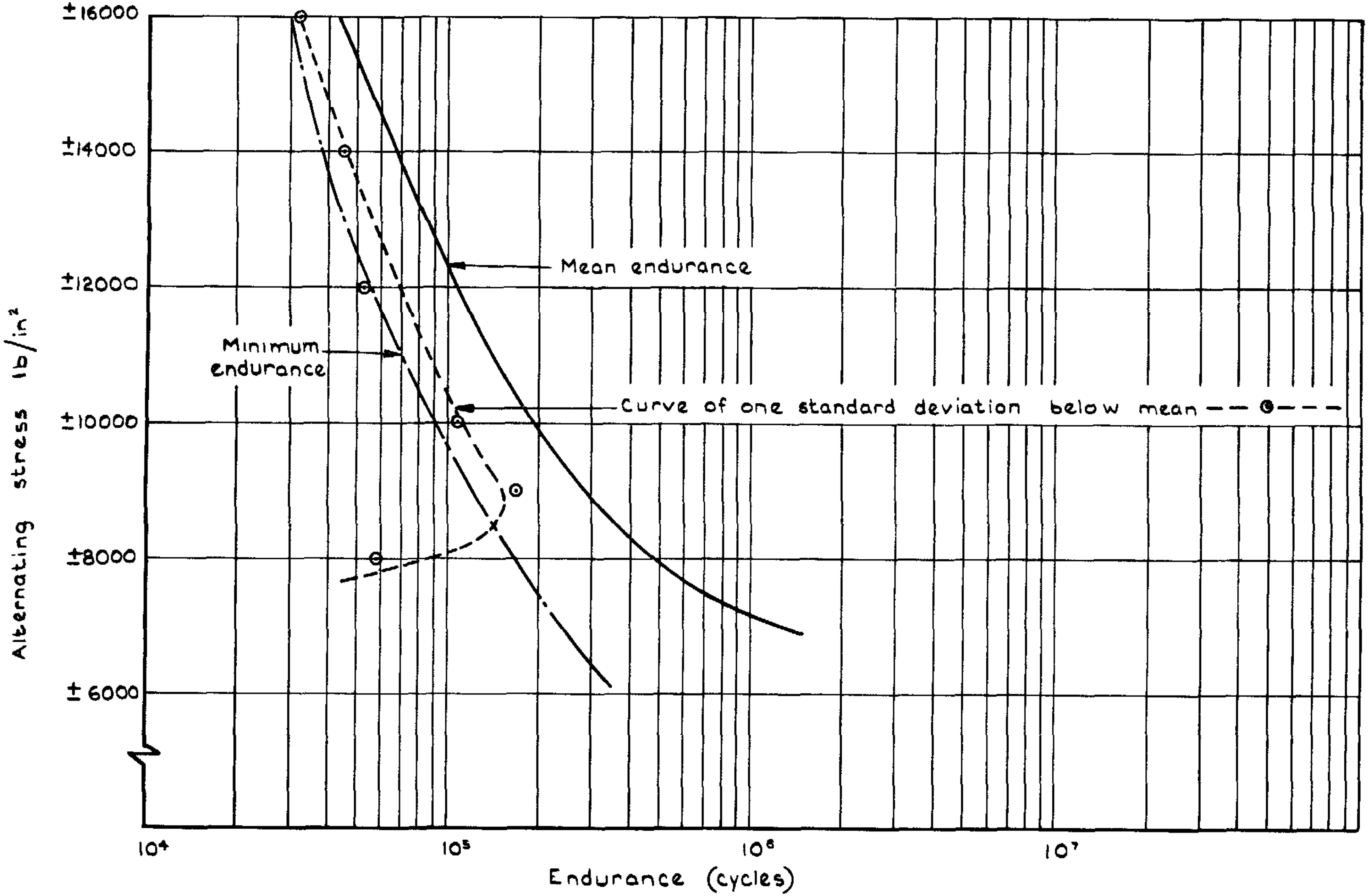


Fig.16 Relationship of mean and mininum endurance curves in terms of standard deviation for the 2·3 notch in DTD 5014 material

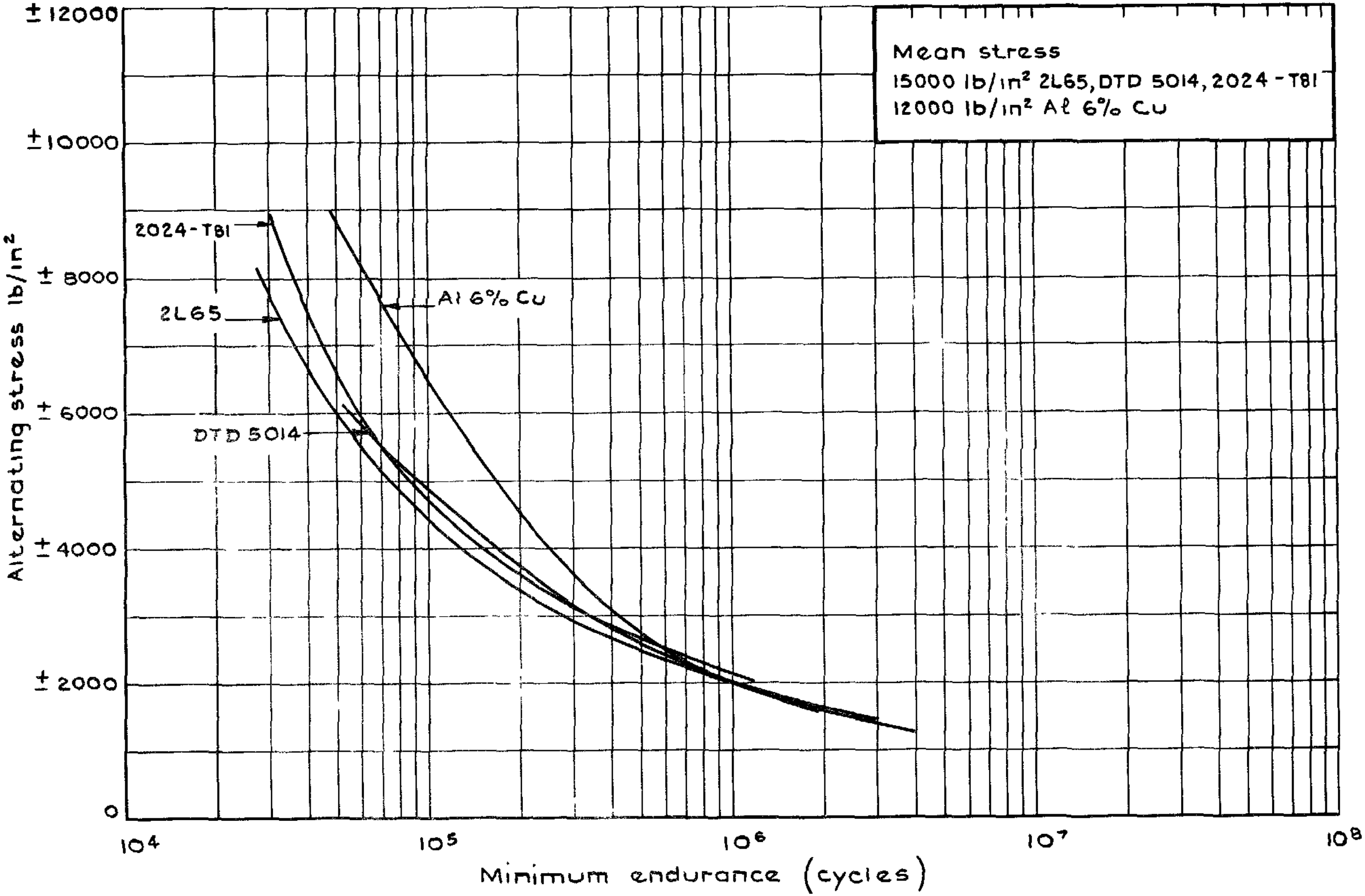


Fig 17 Variation of minimum endurance with alternating stress for lug specimen

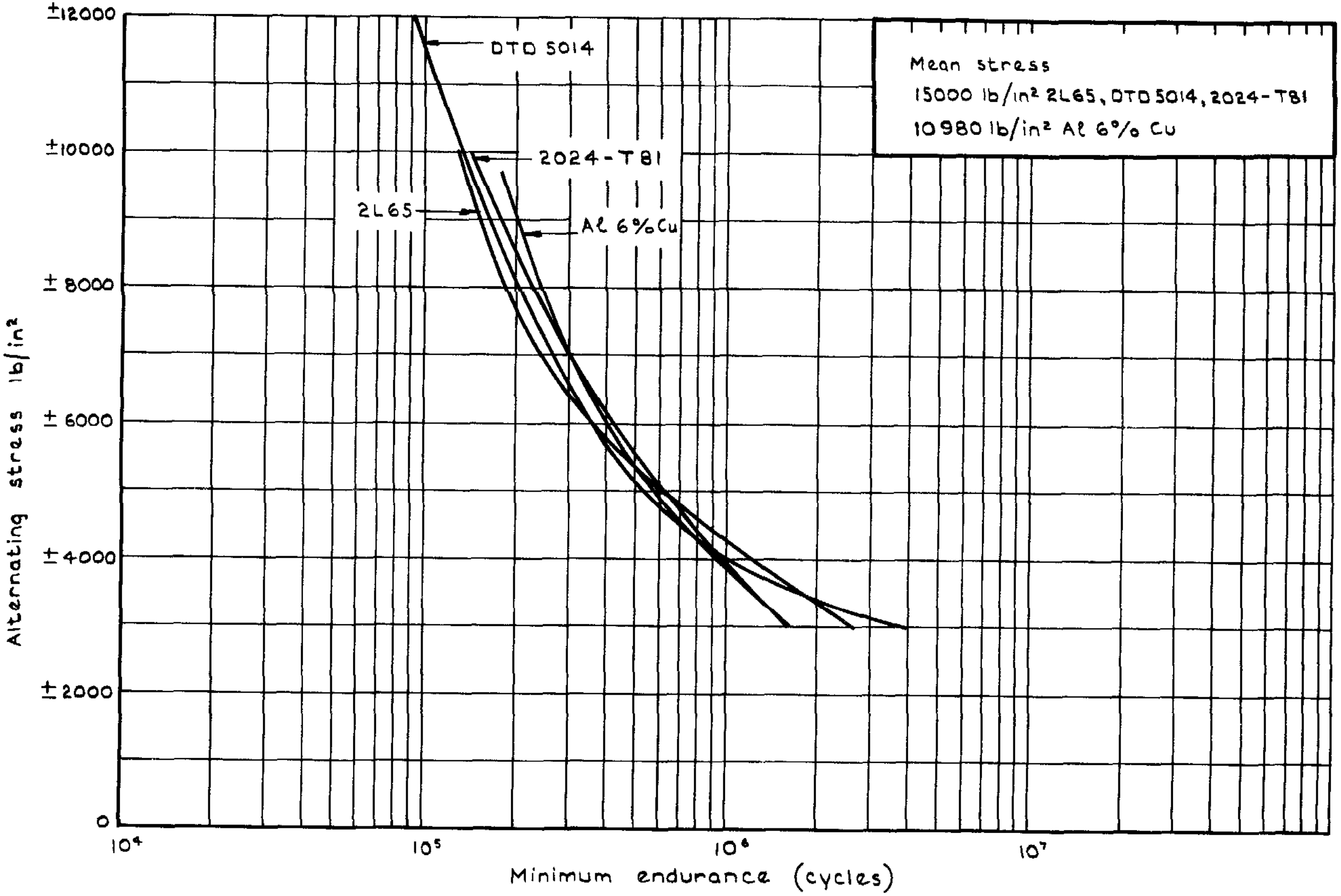


Fig.18 Variation of minimum endurance with alternating stress for joint specimen

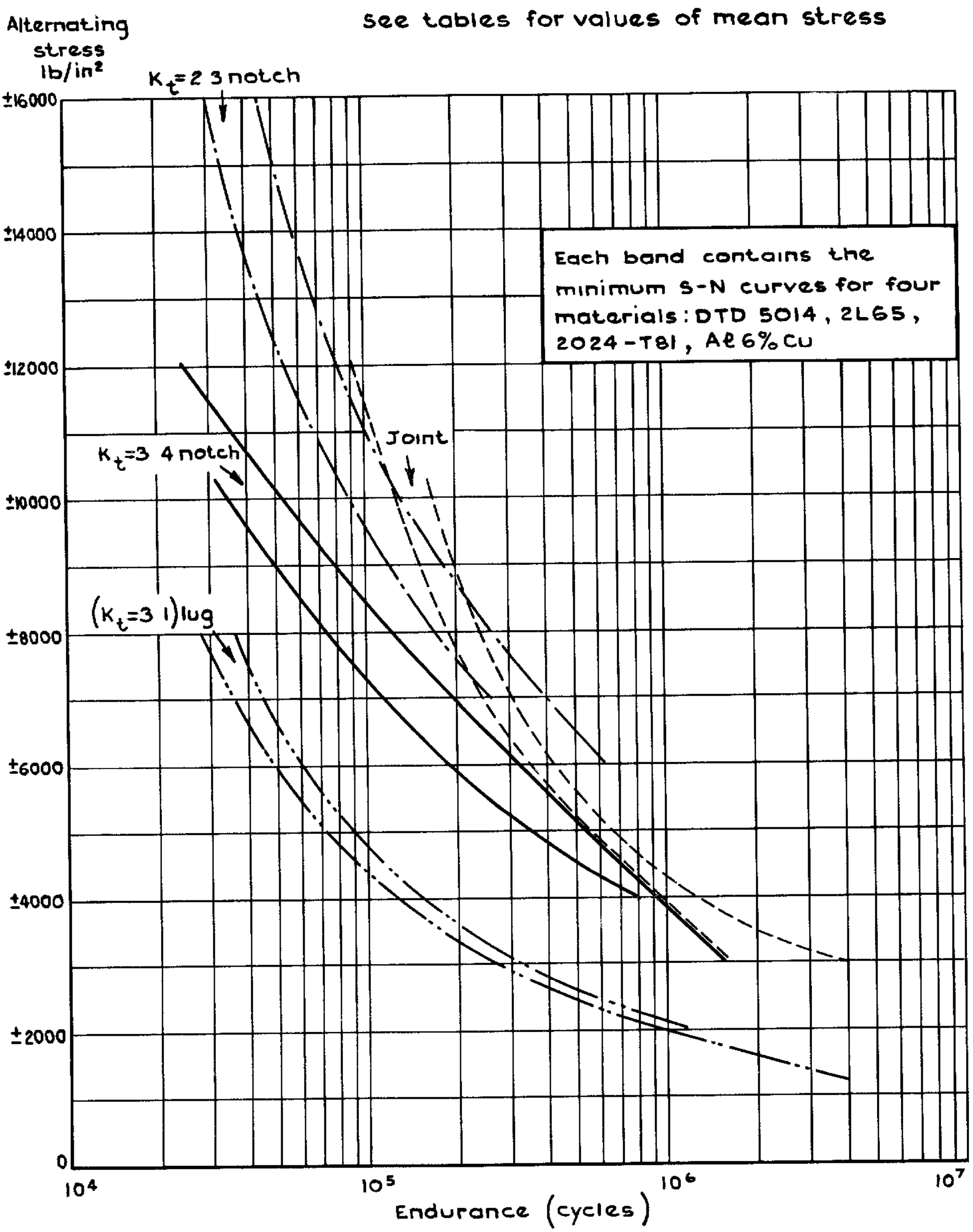


Fig. 19 Variation of minimum endurance with alternating stress for four types of specimen

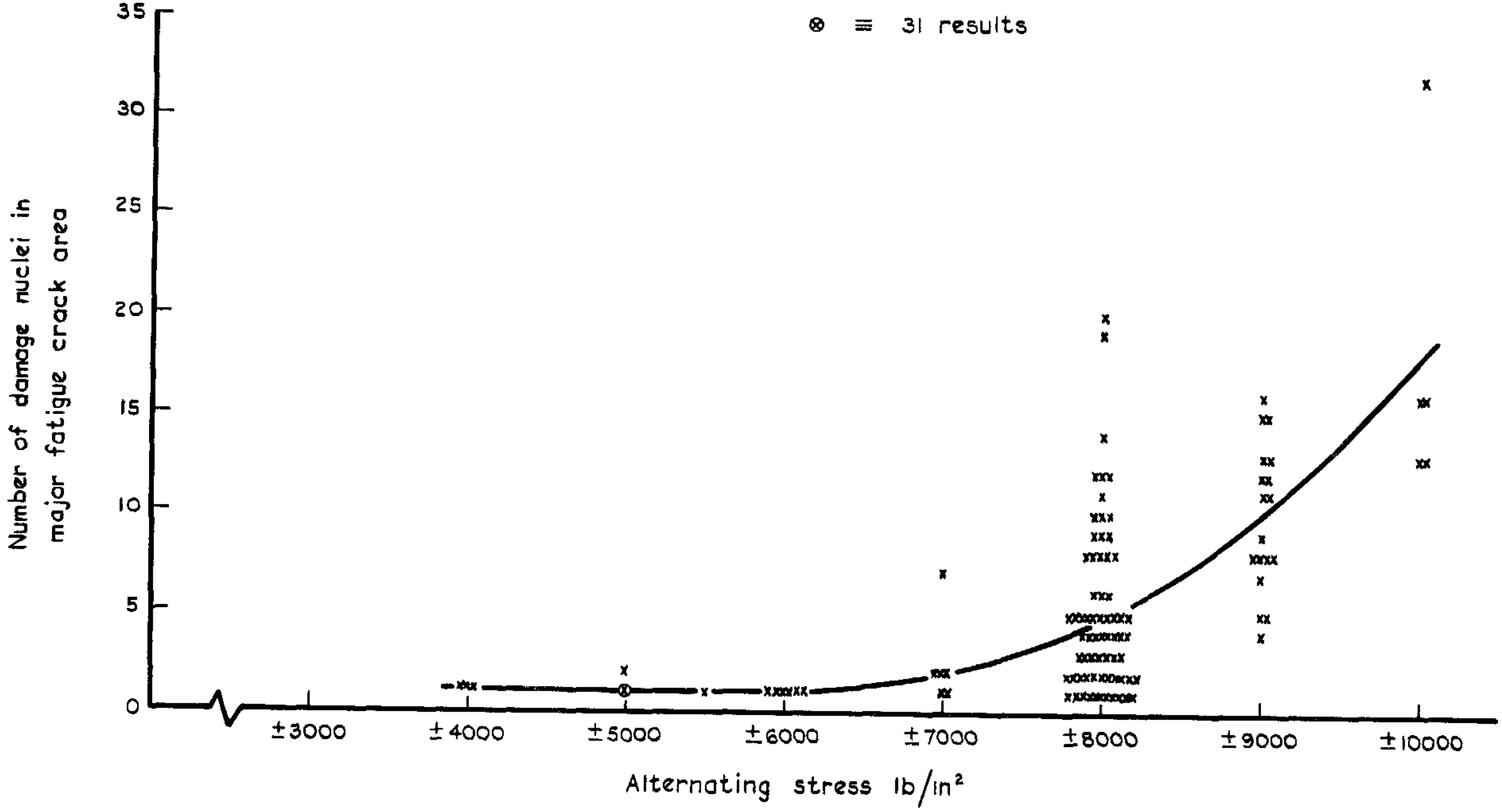


Fig.20 Variation of number of damage nuclei in fatigue crack area with alternating stress for 3·4 notch in DTD 5014 material

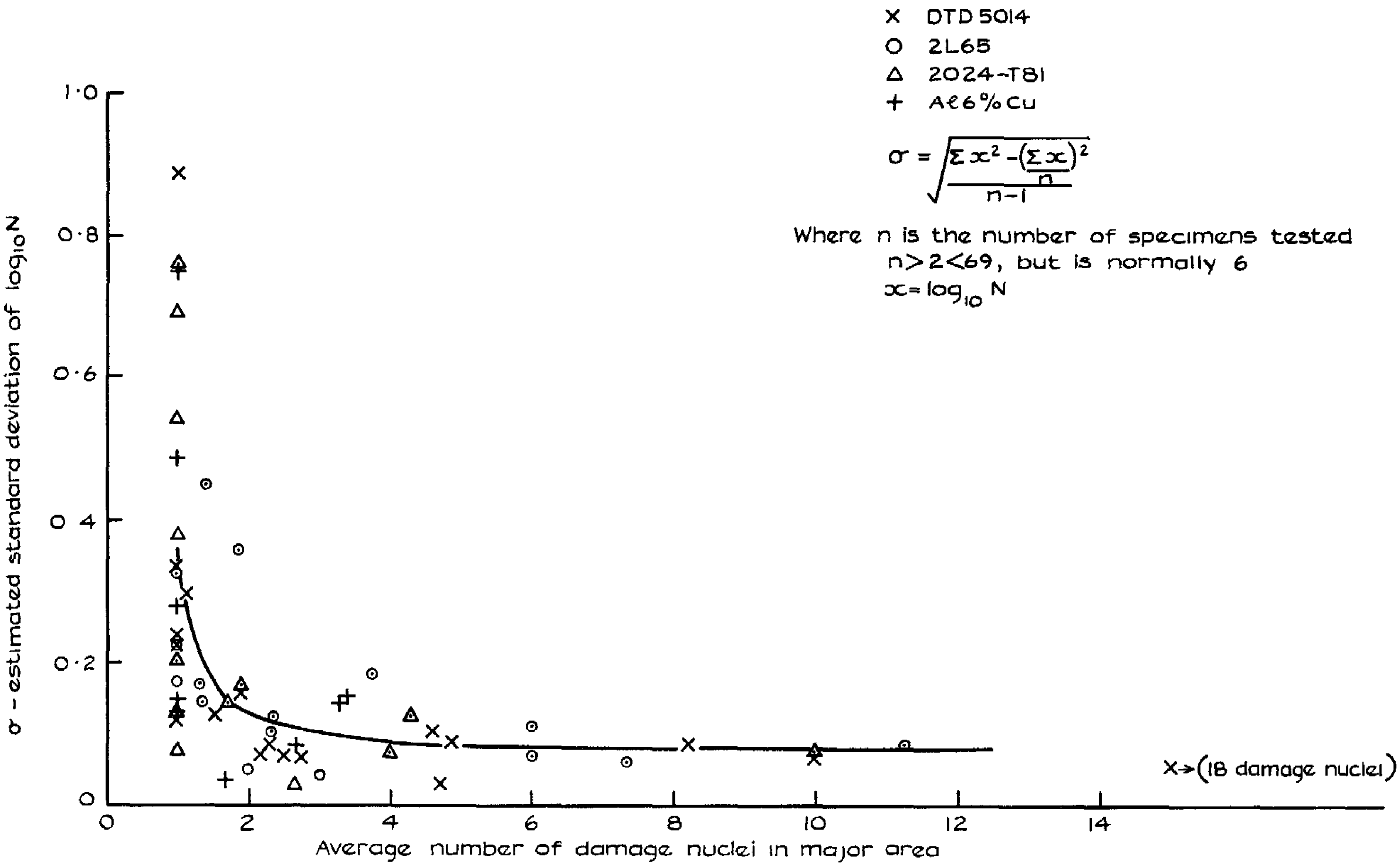


Fig. 21 Correlation of scatter in fatigue endurance (N) with average number of damage nuclei for 2·3 notch, 3·4 notch and lug

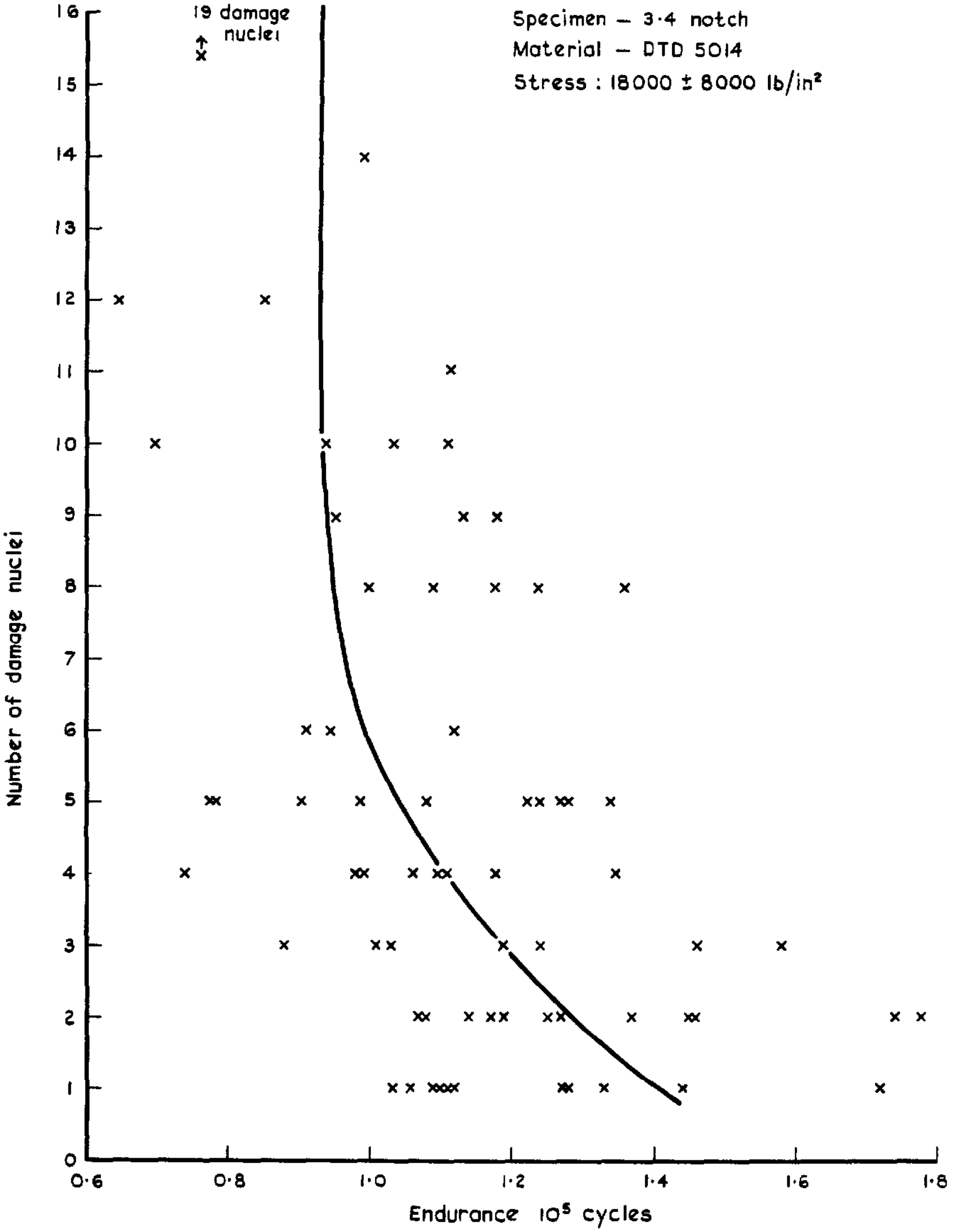


Fig.22 Variation of endurance with number of damage nuclei for a particular stress condition

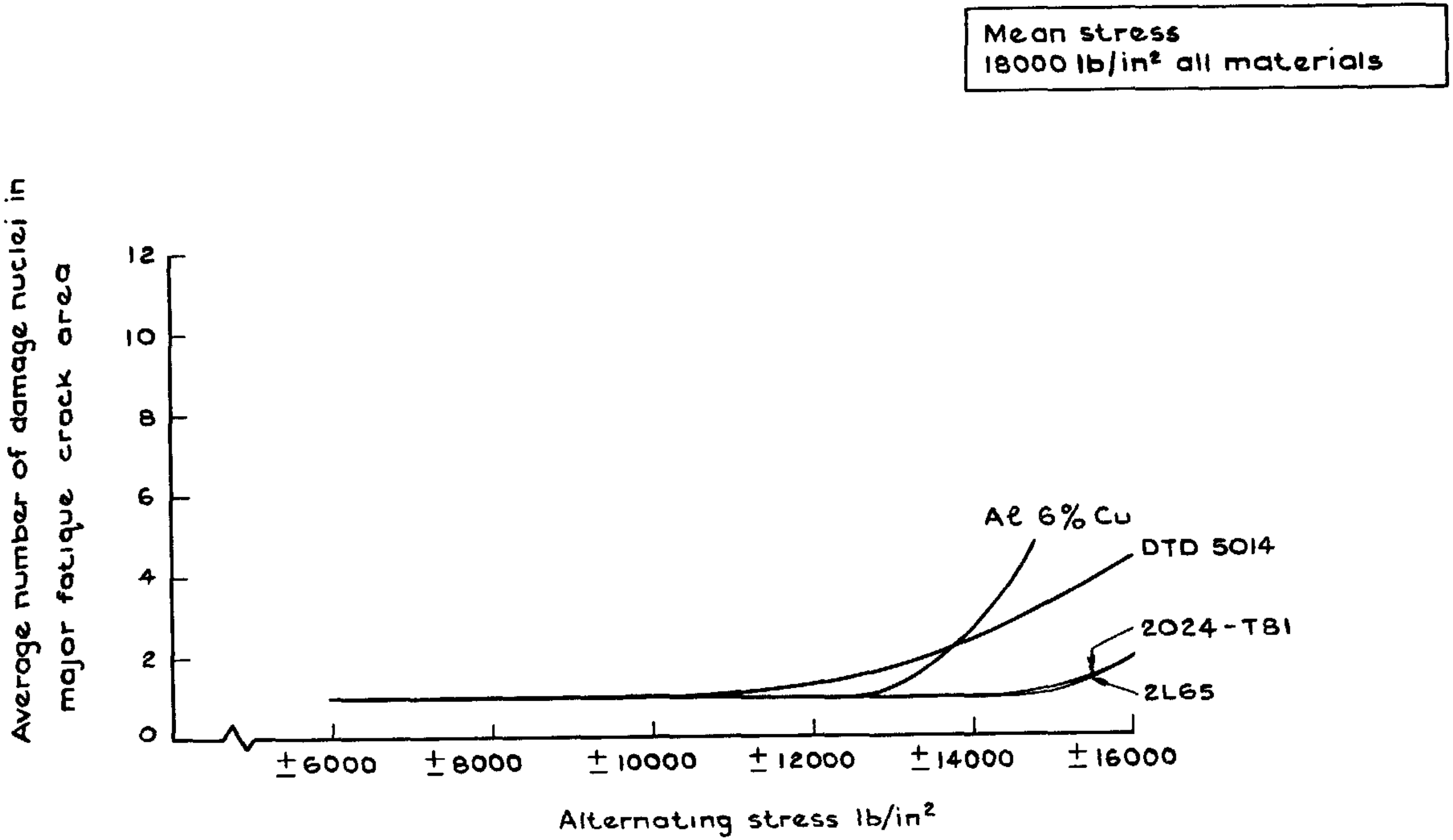


Fig. 23 Variation of number of damage nuclei in fatigue crack area with alternating stress for 2·3 notch

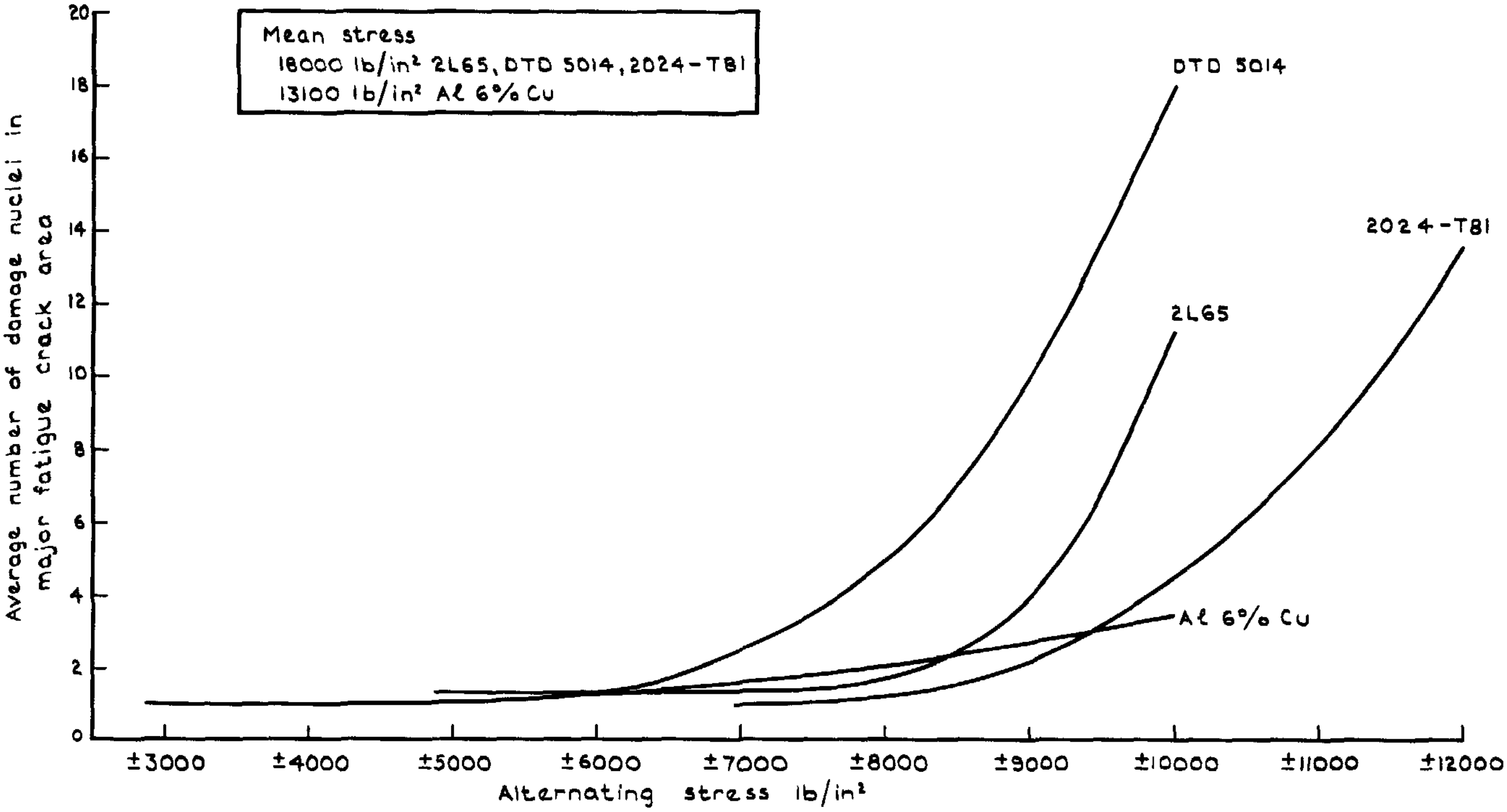


Fig. 24 Variation of number of damage nuclei in fatigue crack area with alternating stress for 3·4 notch

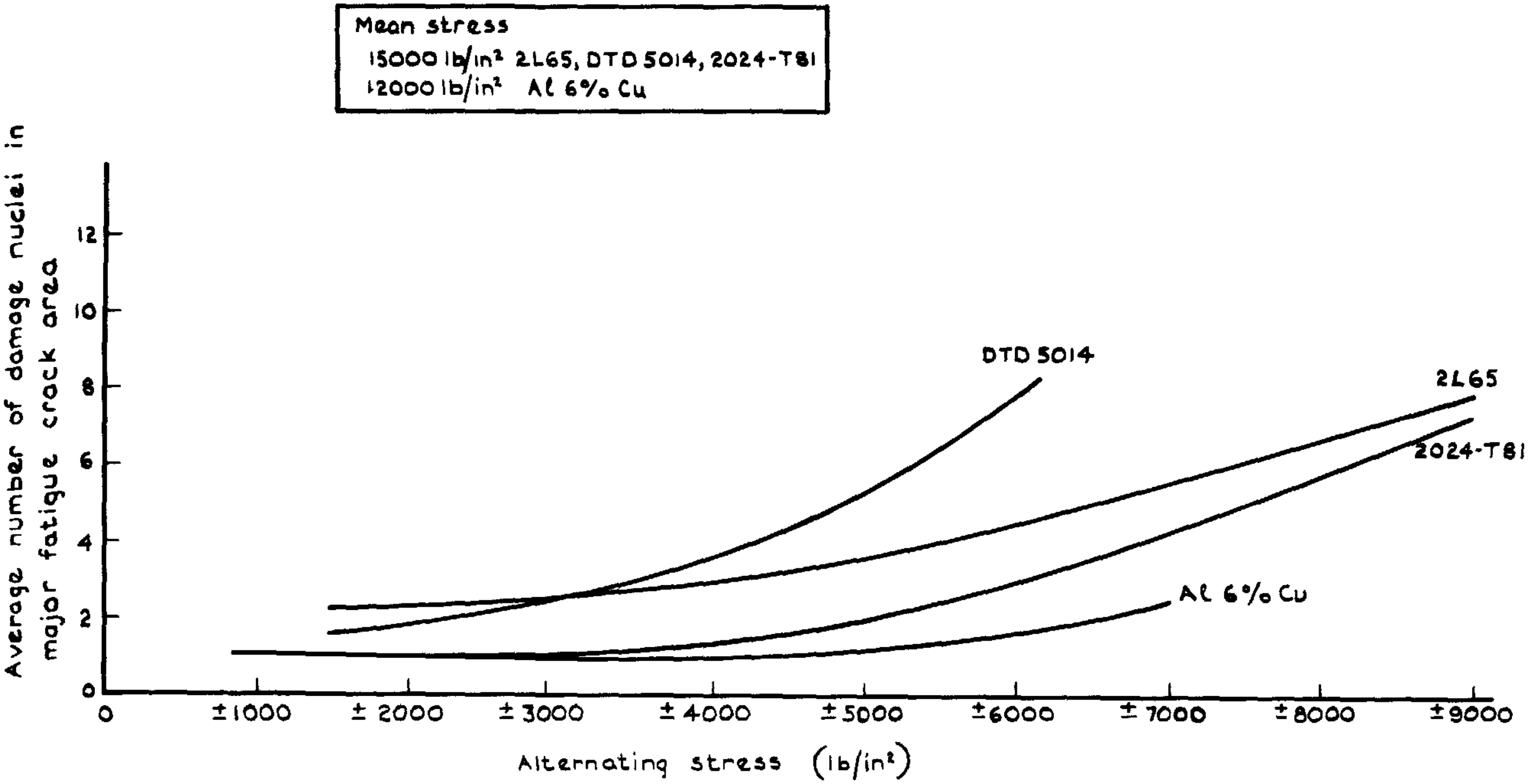


Fig. 25 Variation of number of damage nuclei in fatigue crack area with alternating stress for lug specimen

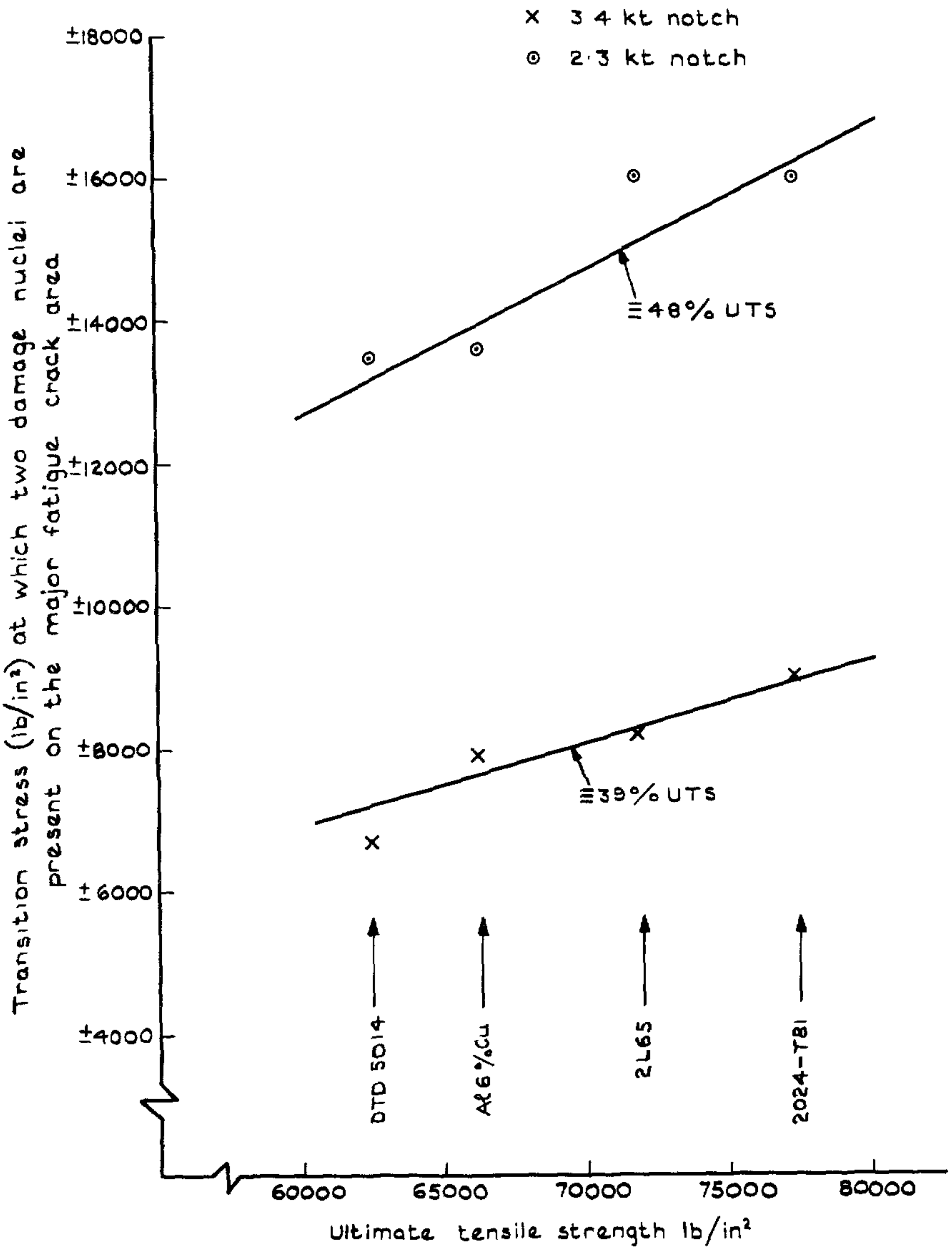


Fig. 26 Correlation of transition stress level for notched specimen with ultimate tensile strength

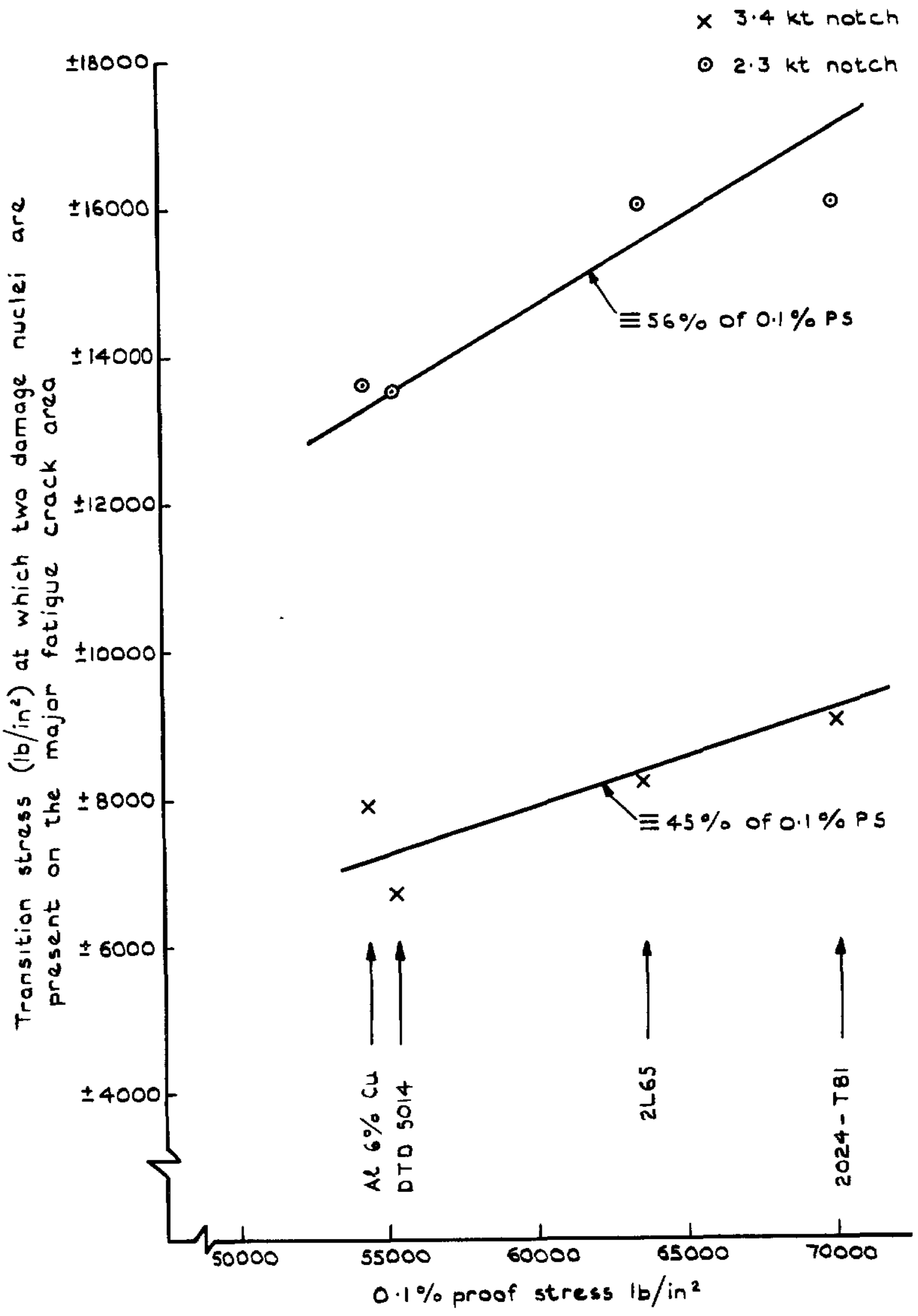
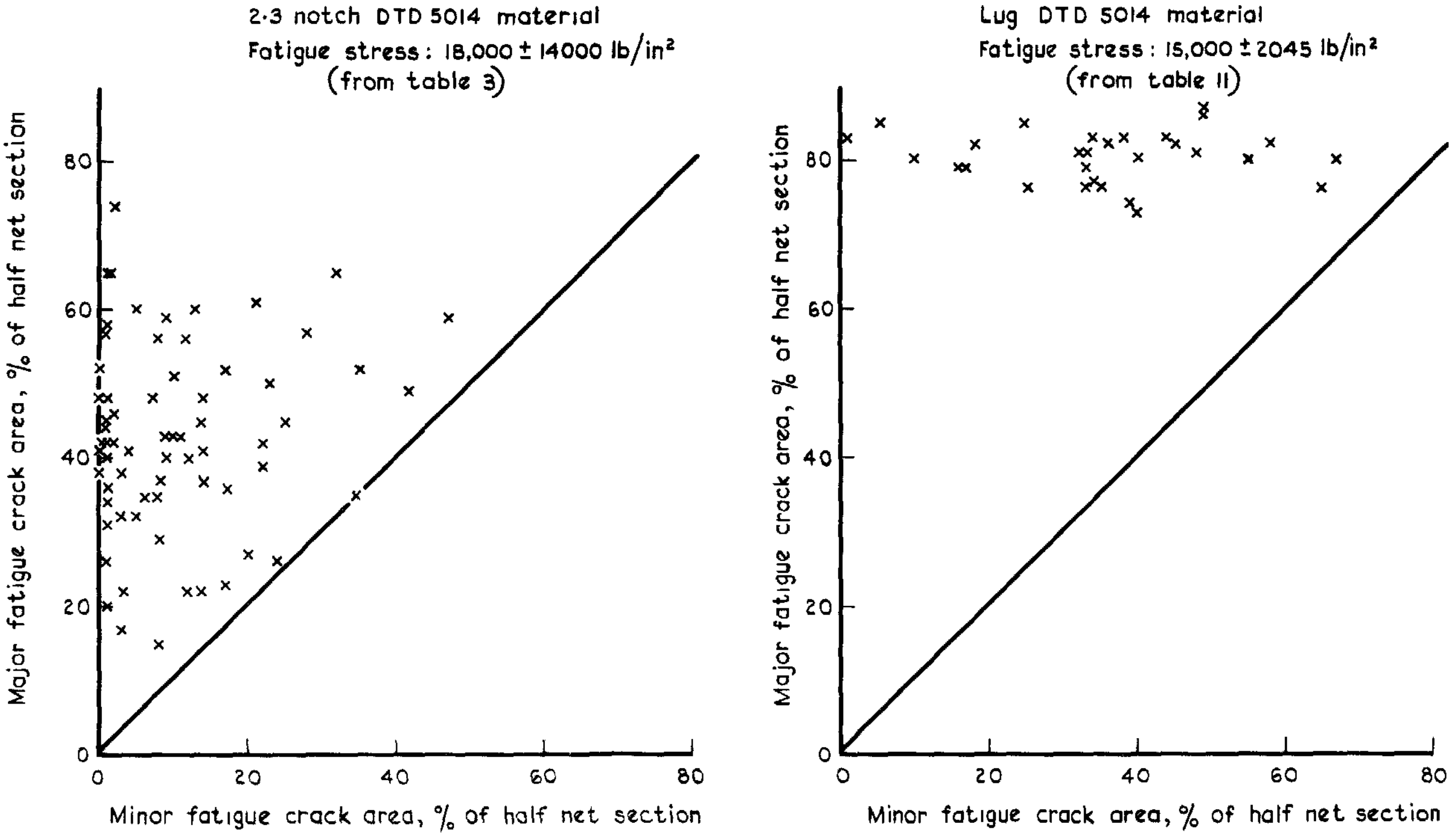


Fig. 27 Correlation of transition stress level for notched specimen with 0·1% tensile proof stress


2·3 notch DTD 5014 material
Fatigue stress: 18,000 ± 14000 lb/in²
(from table 3)

Lug DTD 5014 material
Fatigue stress: 15,000 ± 2045 lb/in²
(from table 11)

Fig.28 Typical variations of major and minor fatigue crack areas for notched and lug specimens

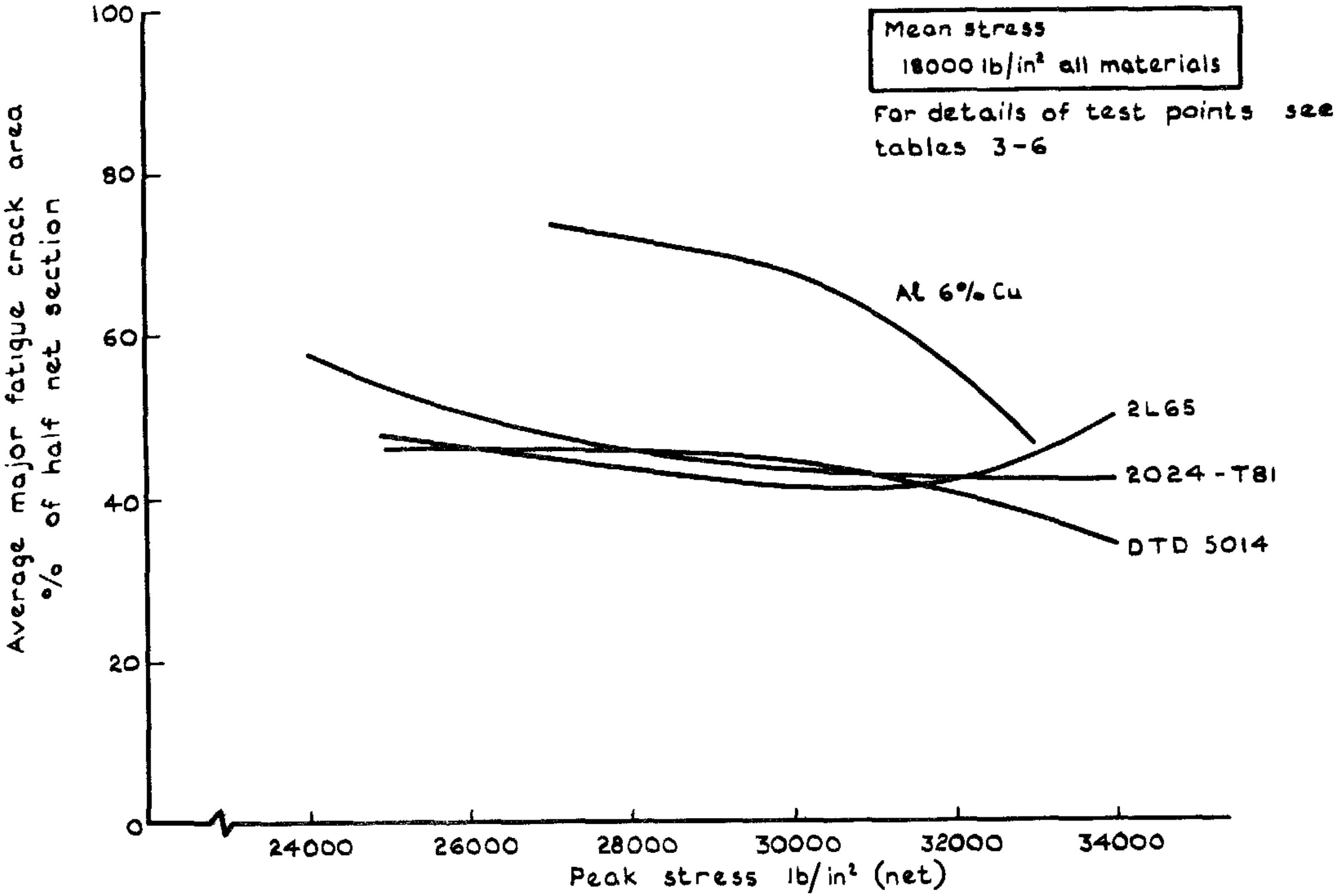


Fig. 29 Variation of major fatigue crack area with peak stress for 2·3 notch

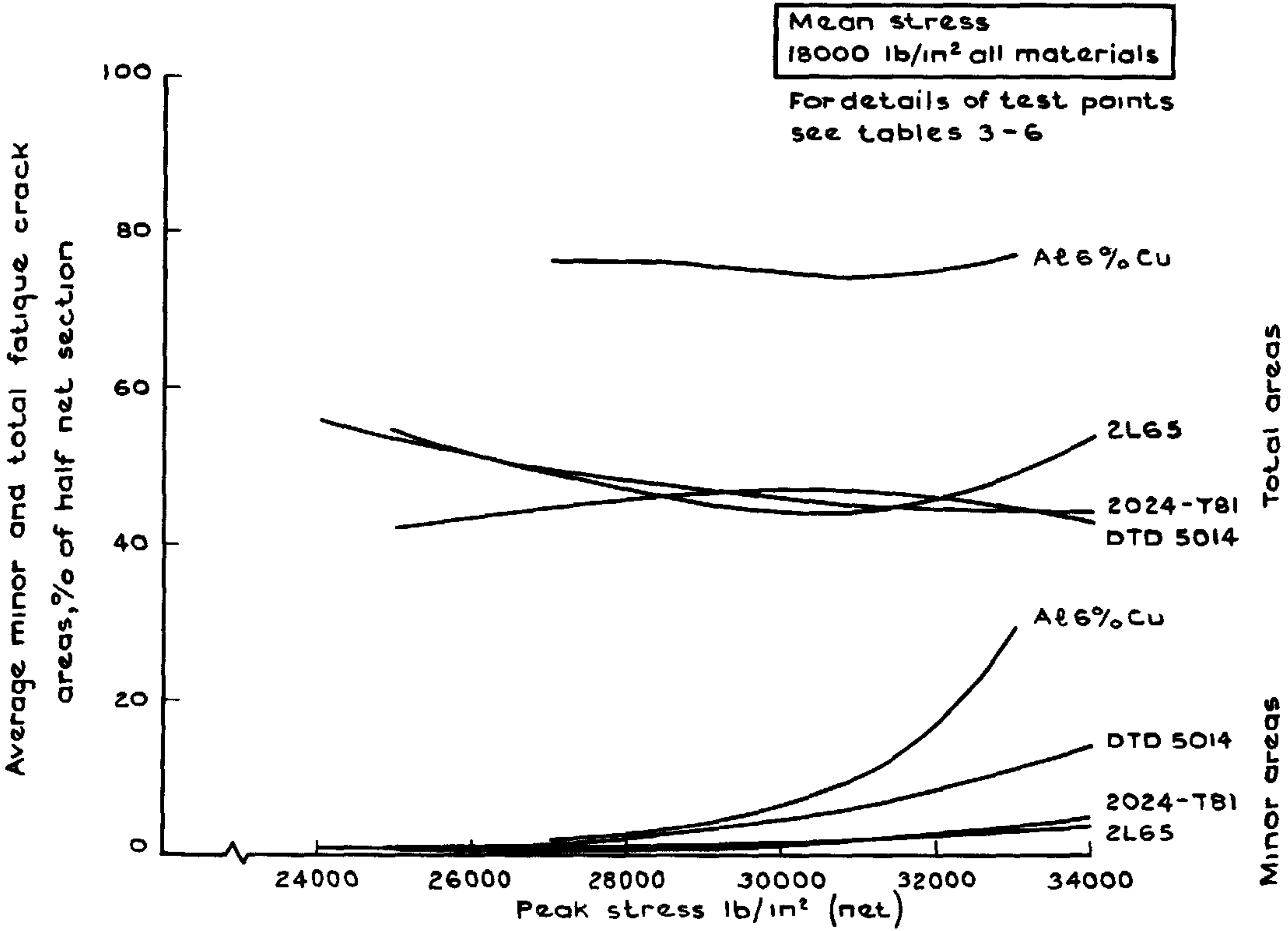


Fig. 30 Variation of minor and total fatigue crack areas with peak stress for 2·3 notch

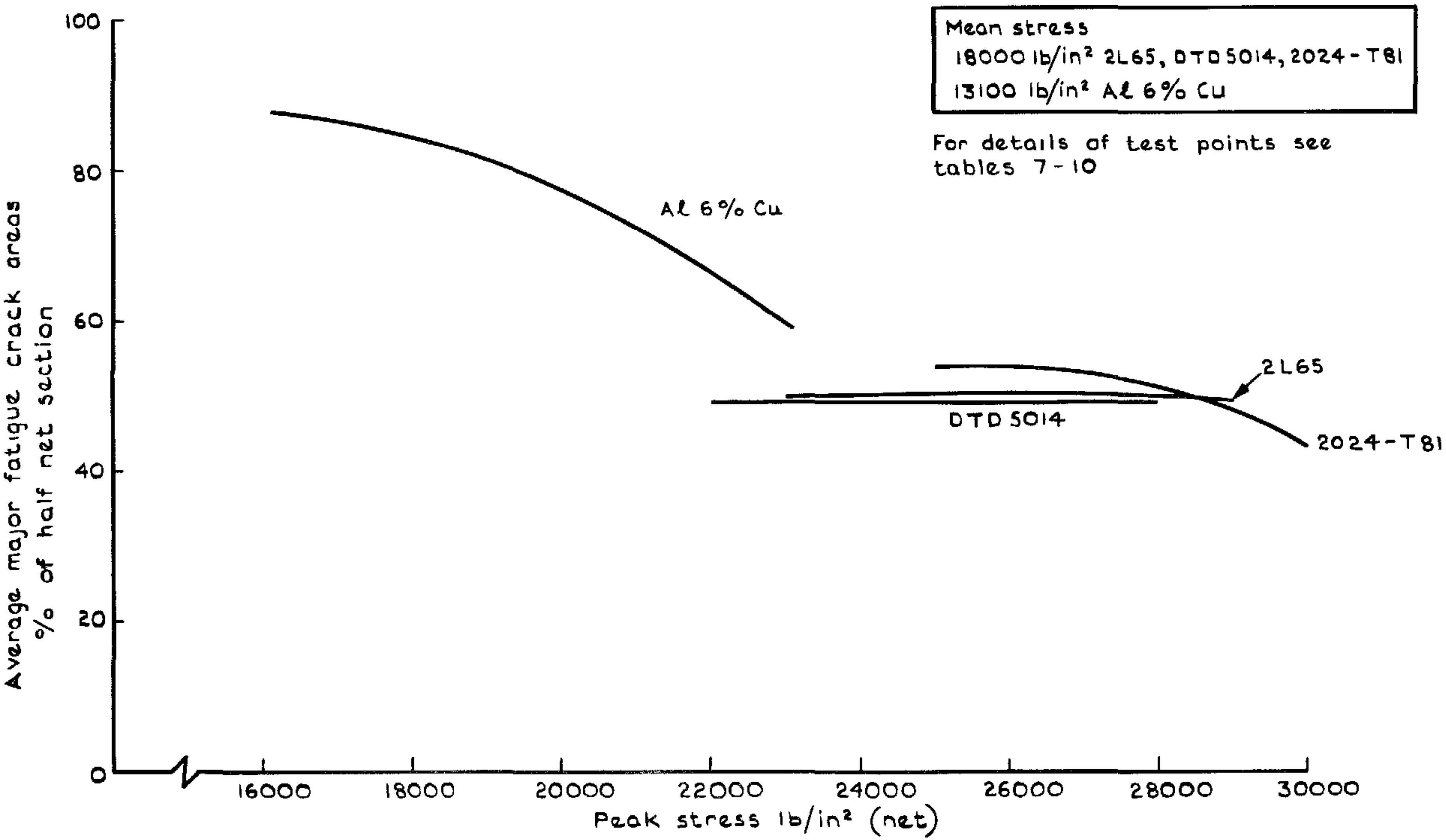


Fig. 31 Variation of major fatigue crack area with peak stress for 3·4 notch

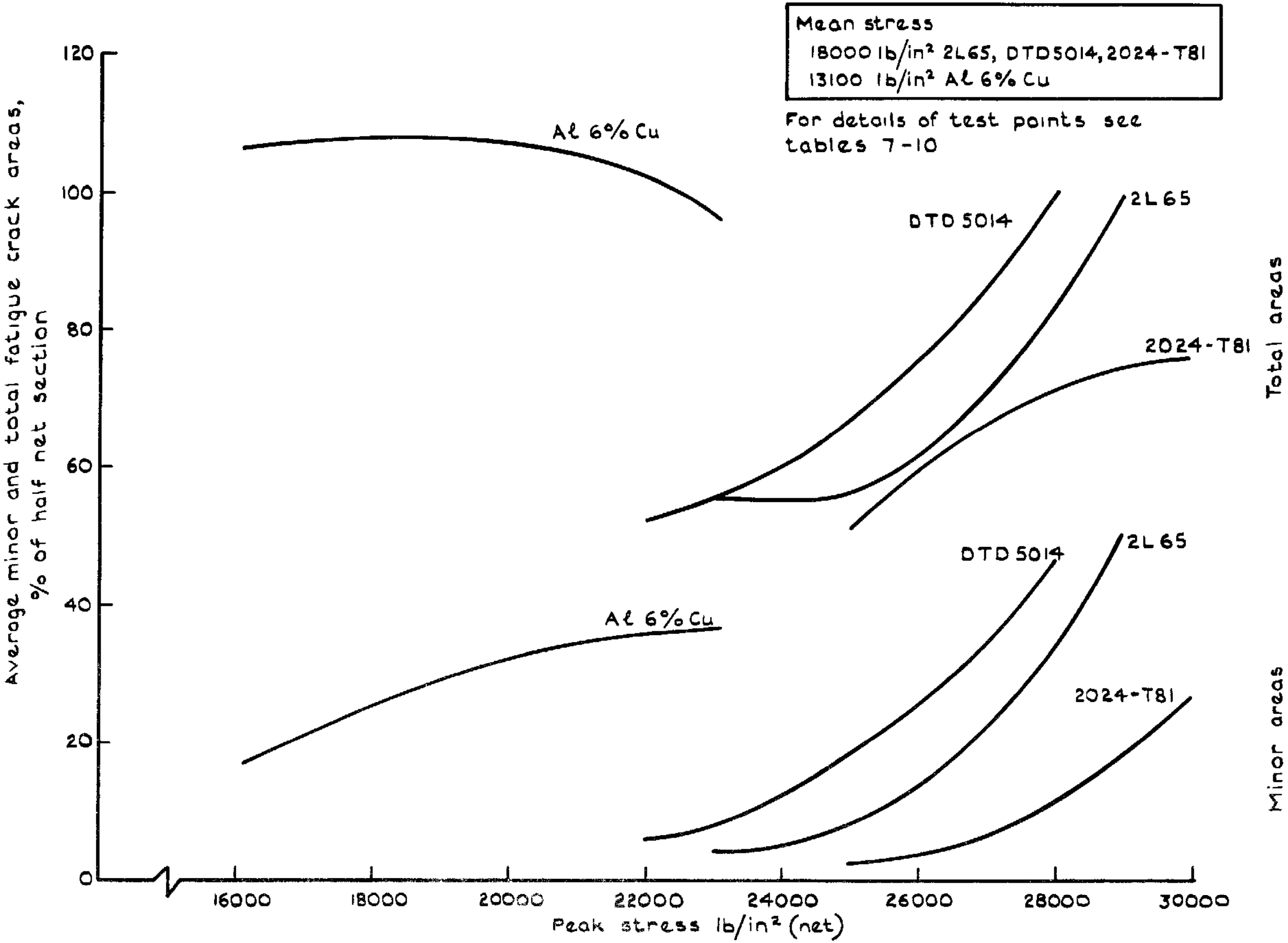


Fig. 32 Variation of minor and total fatigue crack areas with alternating stress for 3·4 notch

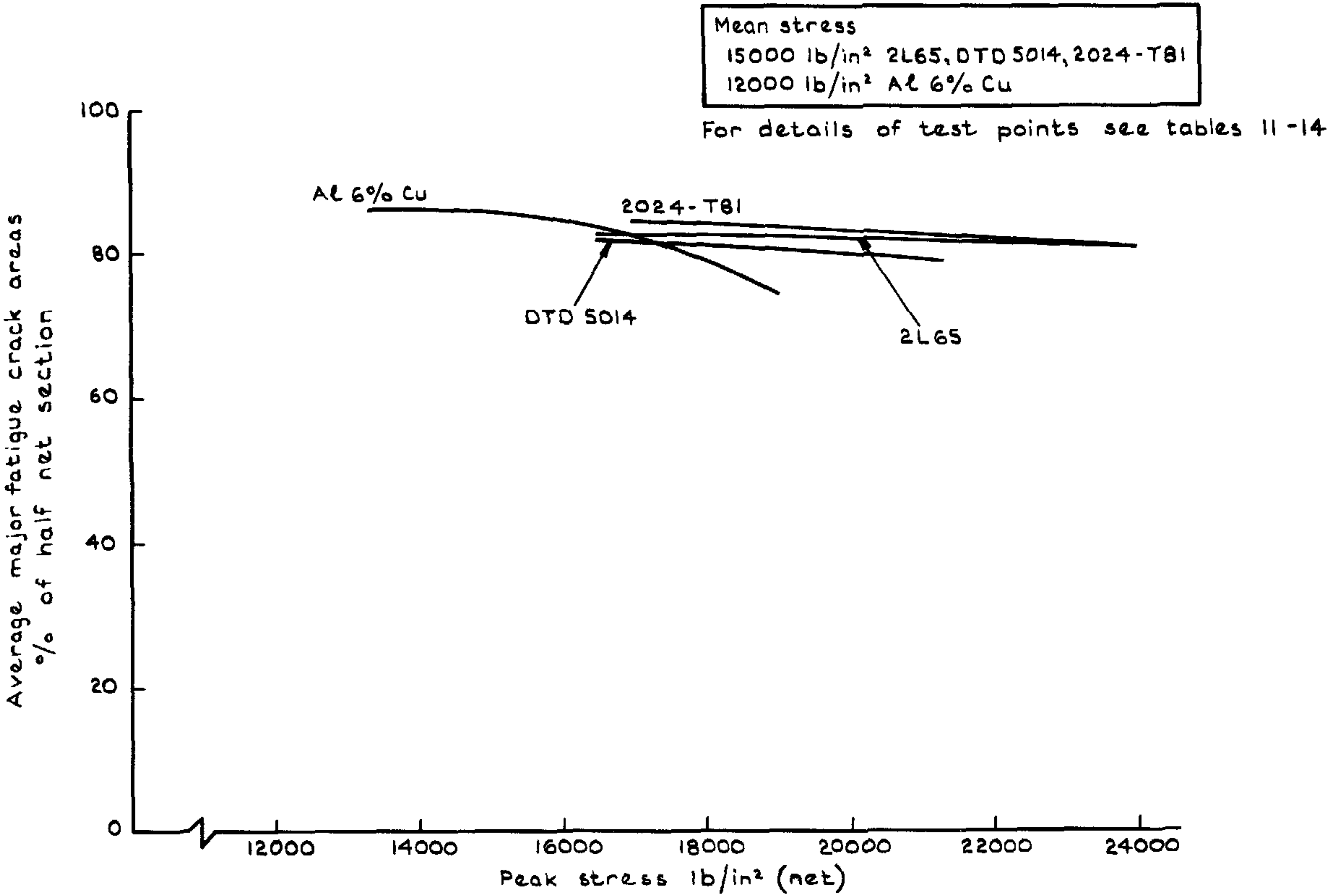


Fig. 33 Variation of major fatigue crack area with peak stress for lug specimen

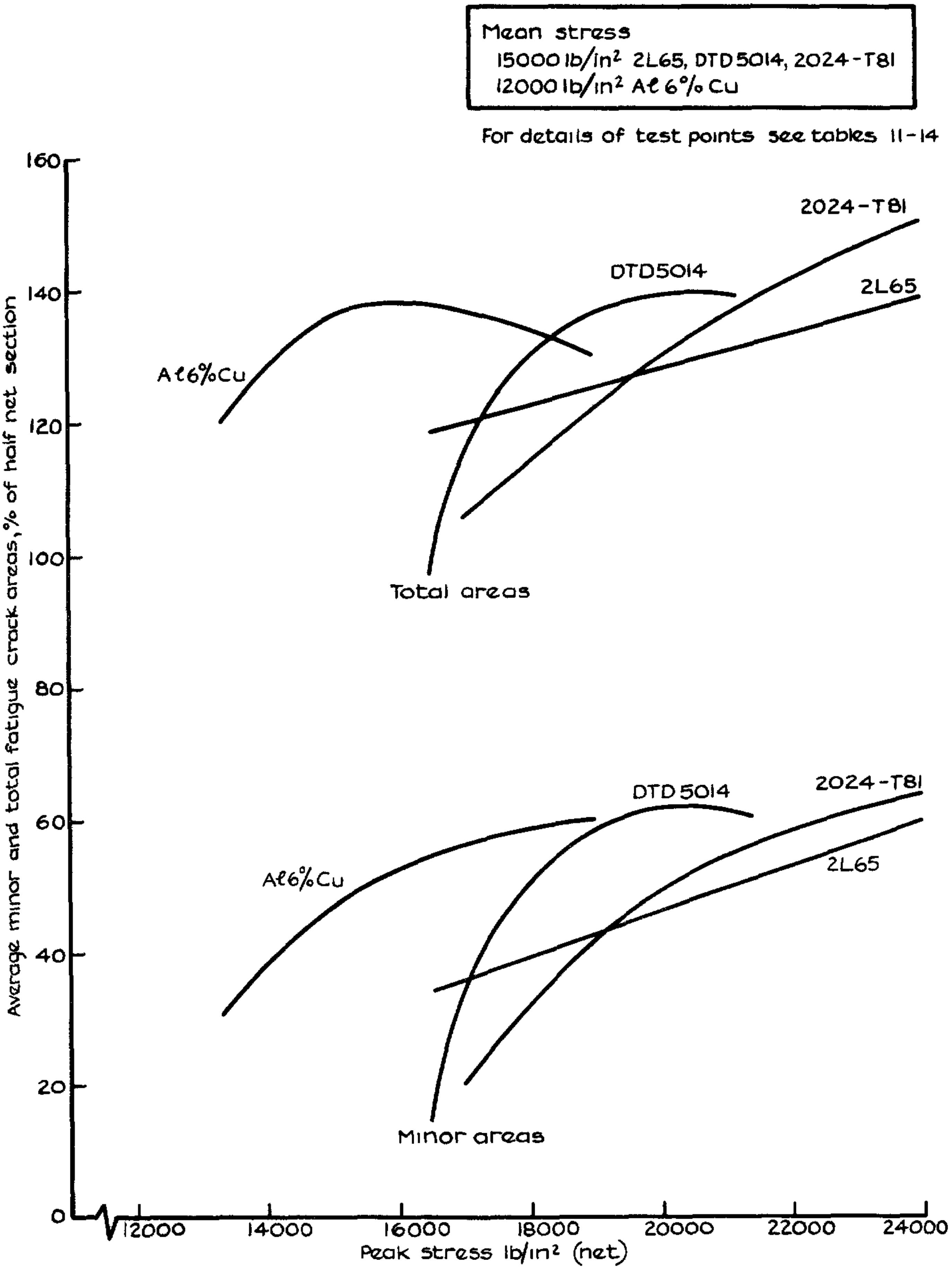


Fig. 34 Variation of minor and total fatigue crack areas with peak stress for lug specimen

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ARC CP No 1259
May 1972

Kiddle, F E

FATIGUE ENDURANCE, CRACK SENSITIVITY AND NUCLEATION CHARACTERISTICS OF STRUCTURAL ELEMENTS IN FOUR ALUMINIUM-COPPER ALLOYS

669 715.3
539 431
539 219.2
539 4.013.3
620.115.842
621.886.4
621 882

Four aluminium-copper alloys in the form of notched, lug and joint specimens were tested under constant amplitude loading at ambient temperature. While there are certain differences in fatigue performance between materials, particularly in the mean endurance and scatter of notched specimens, there is little difference between the materials in terms of the minimum fatigue endurances observed The performance of the different types of specimen are compared and conclusions are reached on the effect of fretting The patterns of nucleation on the fatigue fracture surfaces shows that scatter in endurance is associated with the number of discrete sites of crack nucleation and that in all alloys there is a transition from single to multiple crack nucleation at a value of local stress amplitude related to the static strength Study of fatigue crack areas at failure indicate that crack sensitivity was similar in three alloys and lower in the fourth

ARC CP No.1259
May 1972

Kiddle, F. E

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669 715 3
539 431
539 219 2
539 4.013.3
620 115 842
621 886.4
621 882

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621 886 4
621.882

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