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by

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THE EFFECT OF AN APPLICATION OF HEAT ON THE FATIGUE PERFORMANCE UNDER RANDOM LOADING OF A NOTCHED SPECIMEN OF DTD 5014 (RR58) MATERIAL

by

J. R. Heath-Smith
Judy E. Aplin

SUMMARY

Fatigue tests were made on notched specimens of DTD 5014 (RR58) in fluctuating tension of randomly varying amplitude representing a gust load spectrum. The application of heat for 1000 hours at 150°C at any stage of the fatigue life reduced the remaining life to 25% of expectation and markedly reduced the scatter in life. The effect, which was similar whether the load during heating was zero, tension or compression, is attributed to the rapid initiation of cracking following a period of heating due to loss of work-hardening at the surface of the notch.

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* Replaces RAE Technical Report 71209 - ARC 33733

CONTENTS

Drgs. 011/907124-011/907137

Conversions $1 \text{ ksi} = 1000 \text{ lbf in}^{-2} = 6.894 \text{ MN m}^{-2} = 0.689 \text{ Hb}$

1 INTRODUCTION

The work reported is one part of a programme of basic research into the influence of heat on fatigue in aircraft structures. This programme is concerned mainly with the effect of introducing a single period of heat during room temperature fatigue tests of notched, lug and joint specimens in Al-Cu alloys. The heating period is introduced at various times and is associated with various steady loads.

The tests reported here were those in which randomly varying loads representing a gust spectrum were applied to notched specimens of DTD 5014 material. It was found that the principal effect of the application of heat was to accelerate the subsequent initiation of fatigue cracking and thus to reduce the endurance and the scatter in endurance. This effect was similar to but more pronounced than that reported[1] in the earlier tests in the programme on notched, lug and joint specimens in four aluminium alloys tested under constant amplitude loading.

Recent fractographic and metallurgical observations of the specimens showed that one important mechanism produced by the heating was associated with the loss of work hardening of the machined surface of the notch, and the consequent stimulation of more rapid and more uniform crack initiation. Unlike the results of the tests under constant amplitude, the application of load during heating had no additional effect on the life and this is explained by the argument that, under the load spectrum used, the redistribution of stress by creep was ineffectual.

2 MATERIAL AND SPECIMEN

The specimens were manufactured from three 12 ft (3.7 m) lengths of DTD 5014 (RR58 extruded bar) material of section 2⅛ in × ⅞ in (54 mm × 22 mm) produced commercially from one melt and precipitation heat treated at 200°C to maximum ultimate strength. Tables 1(a) and (b) give the chemical composition and static tensile properties respectively.

Fig.1 is a drawing of the notched specimen used in these tests. It has a theoretical stress concentration of 3.4 times the average stress on the net section. The specimen was loaded axially by clearance-fit round pins on which flats had been machined with the object of improving the fatigue performance of the lug in order to ensure failure at the test section.

3 FATIGUE LOADING

The specimens were loaded axially in a Dowty 20 ton electro-hydraulic fatigue testing machine under a gust load spectrum derived from the Royal Aeronautical Society Data Sheets[2]. The mean stress was 18 ksi (124 MN m^{-2}) at the net section of the notch and the stress spectrum was applied at frequencies within a comparatively narrow band centred on 30 Hz. The spectrum was synthesised by a method[3] in which three stages of randomly varying stress were applied repeatedly in ascending order of rms stress level. Table 2 shows the rms stress level and its duration during each stage. Automatic load control was exercised by an overall adjustment of all three rms levels whenever the rms value of the intermediate stress level, as measured by a Brüel and Kjaer Type 2417 Random Noise Voltmeter on a time constant setting of 30 seconds, was in error by more than ±10%.

In order to check that the overall stress spectrum was satisfactory, it was monitored during each test by counting electronically the number of times the stress exceeded a series of stress increments above and below the mean stress. The upward and downward distributions were approximately symmetrical and Fig.2 shows the upward spectrum obtained by summing lengthy samples from ten of the tests; each of these samples was long enough to give significant numbers of cycles exceeding the highest stress monitored. It is seen that over much of the range of stress amplitude the spectrum is approximately straight, which represents closely a typical gust spectrum, while curvature at each end of the line indicates a curtailment of the numbers of large and small stresses. The number of cycles at stresses below the fatigue limit of the notched specimen was restricted deliberately for economy in testing time, on the argument that they do not contribute greatly to fatigue damage in this type of spectrum. At the other end of the spectrum the restriction on the number and the magnitude of high stresses is a function of the testing equipment; restriction of the magnitude of the cycles was in fact desirable in order that the loading remained in tension with very few excursions through zero load, thus permitting the use of clearance fit pins of the particular design described in section 2.

4 TEST PROCEDURE

All specimens were fatigue tested at ambient temperature under the loading described in section 3. Some specimens were loaded continuously to failure to establish a datum fatigue performance. With other specimens the fatigue testing was interrupted at some stage of the life for a single period of heating under steady loading in order to determine the effect on fatigue life. The effects of three different values of steady load during the heating period were investigated: viz. zero load, tension and compression; the tensile and compressive loads were numerically equal to the mean tension during fatigue.

The three test series corresponding to different values of steady load were each conducted with specimens from a separate bar of material. To establish a datum of fatigue performance five specimens were selected from each bar at about equal spacing along the length for fatigue tests without heating. The logarithm of endurance was plotted against position in the bar and a straight line was fitted by the method of least squares for each bar as shown in Figs.3(a), (b) and (c). This method has been shown by past experience to represent satisfactorily the variation in endurance along a bar of material. The nominal endurances of the remaining specimens was assumed to be that indicated by the straight lines at appropriate positions along the bar. Specimens were then selected for tests with heating so that those tested at the same conditions were widely spaced along the bar.

The stress-temperature sequences used for the three values of steady load during heating are shown in Figs.4(a), (b) and (c). Specimens were loaded in fatigue for a proportion (p%) of their nominal endurance and were then unloaded and transferred to an oven for 1000 hours at 150°C under steady loading. They were then allowed to cool without load applied, and after resting for at least one week were loaded in fatigue to failure. The rest period of one week was intended to ensure that specimens did not differ appreciably in the amount of creep recovery which occurred at room temperature before resumption of fatigue testing. The effect of introducing heat was determined at p = 0, 20, 40, 60 and 80% of the nominal fatigue life on different specimens.

After test, the fracture surfaces were examined at low magnification for information on the number of discrete positions on the notch surface at which fatigue cracking originated (damage nuclei). Measurements were also taken of the area and shape of the fatigue crack at failure.

5 RESULTS

Information on endurance, fatigue crack areas, and numbers of damage nuclei are reported fully in Tables 3, 4 and 5 for tests with zero load, tension, and compression, respectively, during heating.

5.1 Effect of heat on endurance

In Figs.5, 6 and 7 endurance is plotted against the percentage of nominal endurance at which heat was applied for the three values of load during heating. These show that whenever heating is applied, including prior to fatigue, the remaining fatigue life is reduced to about 25% of its expected value. The clarity of this result despite only two specimens at most conditions is due to extremely small scatter after heating compared with the scatter observed in the control fatigue tests without heating, which for reference is plotted at an abscissa of 100%. Although the line for compressive load during heating (Fig.7) is not well defined due to lack of results, it is apparent that the level of load during heating does not affect the result significantly and it is possible to plot all results together on Fig.8 to show the general trend.

5.2 Effect of heat on nucleation of cracks

On the fracture surfaces it was possible to identify regions at the surface of the notch from which fatigue cracks spread, as illustrated in Fig.9. It has been shown[1] that the numbers of these damage nuclei which appear on fracture surfaces can be used as a guide to the variation in the speed of crack initiation between different specimens of one type; rapid initiation is associated with a large number of nuclei. The number of nuclei on each fracture surface was counted therefore to provide evidence of possible differences in initiation between the different bars of material and between specimens tested with and without heat. The histograms in Fig.10 show the frequencies with which different numbers of nuclei were encountered in the three bars of material in fatigue tests with and without heating. In fatigue tests without heating there are differences between the three bars, Bar 61 displaying appreciably lower numbers of nuclei than the other bars. In tests with heating there is greater similarity, the significant change due to heating being an overall increase in the numbers for Bar 61. Reference to Table 3 shows that this increase occurred generally in all tests with heating on Bar 61, including those in which heat was applied as late as 80% nominal life, and indicates that nucleation at some part of the notch surface was still possible at an advanced stage of the life.

5.3 Effect of heat on fatigue crack area

In all specimens a fatigue crack was present at both sides of the notch at final failure. The areas of these cracks were measured separately and are cross plotted as major area and minor area in Fig.11. For tests without heating in Fig.11a the points tend to aggregate in groups corresponding to bars. Whereas Bars 39 and 76 tend to crack equally each side of the notch, Bar 61 shows a definite asymmetry. Fig.11b is the corresponding diagram for heating; all three bars behave similarly and the only significant change is that Bar 61 no longer shows much asymmetry. This is compatible with the information about numbers of damage nuclei discussed in section 5.2 which showed that Bar 61 displayed lower numbers of nuclei than the other bars in tests without heating and that this number increased significantly after heating to correspond more closely with the other bars.

The shape of the fatigue crack area also gives some indication of the pattern of initiation; Fig.12 shows some typical examples from the three bars. In general the first cracks appear to initiate by chance at any position along the notch surface, resulting in a non-uniform depth of the fatigue fracture at failure. This indicates that from among the large number of nuclei distributed along the surface, one or two tended to develop much earlier than the rest. There was a tendency for cracks to be of uniform depth on specimens which were heated early in their life; this suggests that heat caused a large number of nuclei to appear in close succession.

6 DISCUSSION

6.1 Fatigue performance

It has been seen that there is a large reduction in fatigue performance under random loading after a heating period of 1000 hours at 150°C. It is remarkable that at whatever stage of the life heat is applied the remaining life is reduced to an almost constant proportion (25%) of expectation but it seems unlikely that this is the result of a linear acceleration of all subsequent phases of fatigue damage and, indeed, this would not explain the marked reduction in scatter.

It is generally accepted that scatter is associated mainly with the initiation of cracks at a surface rather than with their propagation through the material. In thick specimens, particularly, it might be supposed that some scatter arises in crack propagation due to variation in the shape of the crack front. However, considering that the pattern of cracking was modified differently on the three bars by heating (section 5.3) and yet the effect of heat on endurance was similar on all bars, it can be concluded that the pattern of cracking does not contribute significantly to scatter in endurance.

The large reductions in endurance and in scatter suggest that crack initiation occupies a large proportion of the endurance in tests without heat and that this phase is largely eliminated by the prior application of heat. In order to assess the ability of this simple model to explain the observed behaviour shown in Fig.8, consider a set of specimens which behave identically and for which 75% of the life is spent in initiating a crack. Fig.13a illustrates the effect of applying heat once at different stages of the life, on the assumption that heating effectively concludes crack initiation and does not affect subsequent crack propagation. The diagram is not unlike the results obtained except that in practice life is affected by heat applied later than 75% life. It seems necessary therefore to assume a more complex specimen behaviour based on the observation in section 5.3 that, in tests without heat, initiation arises progressively along the notch surface so that, during part of the life, initiation and propagation of cracks take place concurrently at different parts of the fracture surface. The fatigue life can be conveniently regarded then as consisting of three phases: an initial phase when no crack is present but nuclei are forming, a second phase in which a crack is propagating from part of the notch surface and nucleation is proceeding elsewhere on the surface and a third phase during which nucleation is complete and the crack is propagating from the whole notch surface. On this basis we can construct a new diagram, Fig.13b. During the first phase the application of heat is followed by rapid initiation at many points of the surface with a consequent shortening of life as in Fig.13a. In the second phase, the effect of heat is confined to the uncracked part of the surface; the later in this phase that the heat is applied, the more extensive is the cracking which is already present, and therefore the smaller the effect on endurance of promoting initiation. Consequently the line in Fig.13b becomes shallower. In the third phase, heat has no effect, the supposition being that heat affects only crack initiation. This phase is short, however, as not much crack propagation remains once an asymmetric crack extends across the full width. Reference to the test results in Figs.5 to 8 shows that for reasonable agreement with the hypothetical diagram it is only necessary to assume that the third phase is negligibly short. That this is so is supported by the results of some of the tests without heat, notably from Bar 61, in which the third stage was not reached before failure (Fig.12).

It is concluded that the effect of heat was to promote rapid crack initiation and that the almost linear reduction in remaining fatigue life is characteristic of thick sections in which initiation and propagation both occur during much of the life. The next section is a discussion of mechanisms which might be responsible for this observed behaviour.

6.2 Mechanisms of fatigue-heat interaction

One factor of potential importance in fatigue-heat interaction is the redistribution of stress across a section by creep, resulting in a change of local residual stress at the notch surface or at the tip of a crack growing from the notch. From studies of cumulative fatigue damage[4] it is known that residual stress due to local yielding under the applied fatigue loads has a significant influence on fatigue performance and it has been suggested[5,6] that the modification of residual stress by creep during a heating period may therefore give a significant interaction. However, the modification of residual stress by creep will be effective only if it remains unaltered by the subsequent fatigue loading, and for the present tests it is readily demonstrated that the maximum stress cycle of the spectrum (18 ± 18 ksi), a value which is approached frequently during the fatigue life, is more than sufficient to modify the residual stress after creep.

This is illustrated in Figs.14a, b and c which show diagrammatically the variation of local stress at a stress concentration of 3.4 for specimens which are first exposed to heat at nominal stresses of 0, 18 and -18 ksi respectively and are then loaded to the nominal peak stress of 18 + 18 = 36 ksi. It is assumed that the period of creep is effective in fully redistributing stress across the net section and, in addition, residual stresses from manufacture are neglected as these would not affect the outcome of the argument. In Fig.14a heat is applied at zero load at A and, after cooling, the specimen is loaded to a nominal 36 ksi which takes the notch stress through yield to B. In Fig.14b the specimen is initially loaded to a nominal 18 ksi which takes the notch stress just past yield to C and is then heated for a period during which creep redistribution reduces the notch stress from C to D, the average stress on the net section. On unloading, the stress reduces to E with some compressive yielding and the application of a nominal 36 ksi then takes the stress through tensile yield to F. In Fig.14c the specimen is loaded to a nominal -18 ksi taking the notch stress past compressive yield to G. During heating, compressive creep relaxes the stress to H and on unloading, the stress rises to J. Application of a nominal 36 ksi further increases the notch stress through tensile yield to K. Although in the three cases the residual stresses after heating are different (points A, E and J), once the highest load in the fatigue spectrum is applied the local stress state is similar in all cases in being substantially in tensile yield (B, F and K). Any slight differences would tend to disappear under subsequent fatigue loads, the highest of which is sufficient to produce reversed plastic cycling at the notch.

The argument that changes in residual stress cannot account for fatigue-heat interaction in the present tests is supported by two aspects of the test results. First, referring again to Fig.8 in which the effects of heat on endurance are shown for all levels of load during heating, it is seen that the result is insensitive to load level. Second, the same diagram shows that the trend of endurance with the stage of life at which heat was applied is continuous, including the special case of application at 0%, i.e. heating prior to fatigue. It follows that prior application of load was not necessary to the observed effect of heat, which cannot arise therefore from changes in residual stress.

It was observed above that in Fig.8 the trend of endurance with the stage of life at which heat was applied was continuous from 0%. This suggests that the effect of heat at any stage of the life may be to change some condition of the surface of the notch resulting from manufacture. Evidence on this point is provided by results of metallurgical examination of some of the specimens, carried out by Materials Department, RAE[7]. This work showed that, for specimens as manufactured, the surface of holes which had been drilled and reamed had work affected zones 30-40 μm deep in which the original grain boundaries were replaced by sub-grain boundaries by a fragmentation process, and in which the hardening precipitate had been destroyed. Micro-hardness measurements indicated a hardness at the surface of ∿300 DPN reducing through the zone to the interior-material value of ∿130 DPN. Heating for 1000 hours at 150°C produced a relatively coarse secondary precipitate at the new sub-boundaries and reduced the hardness of the surface zone to a value similar to that of the interior material. This evidence of changes in the surface condition due to heating was supplemented by fractographic examination. This showed that in specimens not exposed to heat, fatigue cracks had initiated below the hard surface layer produced by the drilling and reaming. By comparison, in specimens which had been heated the cracks appeared to originate at the surface itself.

This metallurgical evidence is consistent with the hypothesis that the effect of heat is to promote rapid crack initiation due to a change in a surface condition resulting from manufacture. It indicates that rapid crack initiation results from softening of the work hardened layer which normally resists cracking so strongly that cracks initiate below the surface.

In concluding that the observed fatigue-heat interaction is due to loss of hardness at the notch surface and is uninfluenced by changes in residual stress due to creep, it should be observed that the latter mechanism may well play an important part in fatigue-heat interaction under different stress conditions: in tests with loading of moderate, constant amplitude for example[1] the influence of stress level during heating is quite marked and is consistent with the modification of residual stress by creep. An important aspect of the present tests is the demonstration and identification of a fatigue-heat interaction in which creep plays no part, leading to the recognition of two independent mechanisms of interaction: loss of work hardening by heat, and redistribution of stress by creep.

7 CONCLUSIONS

Fatigue tests were conducted on notched specimens of DTD 5014 (RR58) material in fluctuating tension of randomly varying amplitude to determine the effect of a single period of heat at constant load for 1000 hours at 150°C during the life.

(1) Heating at any stage of the life reduced the remaining life to about 25% of expectation with extremely low scatter.

(2) The reduction in life was due to the rapid initiation of cracks following heating. This was associated with secondary precipitation and loss of work hardening at the surface of the notch.

(3) The reduction in endurance was unaltered by the application of tensile or compressive load during heating. This is consistent with the argument that, under the load spectrum used, the modification of residual stress by creep is ineffectual.

Acknowledgement

The authors gratefully acknowledge the contribution of metallurgical and fractographic observations by Mr. P. J. E. Forsyth of Materials Department, RAE.

Table 1

(a) Chemical composition

Element	% by weight
Cu	2.33
Mg	1.64
Si	0.15
Fe	1.07
Mn	0.08
Zn	0.09
Ni	1.28
Ti	0.03
Al	Remainder

(b) Static tensile properties

Bar No.	0.2% PS ksi	UTS ksi	Elongation on 1 in %
61	55.3	62.0	10
39	57.1	63.6	12
76	55.7	64.7	12

Table 2

APPLIED STRESS SPECTRUM

Stage	Duration % of programme	Alternating stress level ksi (rms)
1	71	2.4
2	26	3.8
3	3	6.0
	Overall	3.0

Average duration of one programme = 458 seconds ≡ 13730 cycles

Table 3

FATIGUE TESTS WITH ONE APPLICATION OF HEAT (BAR 61)
1000 HOURS AT 150°C AT ZERO STRESS

Specimen number†	% of nominal endurance at which heat was applied P	Actual endurance 10^6 cycles	$\frac{\text{Actual endurance}}{\text{Nominal endurance}}$ %	Major fatigue crack		Minor fatigue crack	
				Area of crack on half the net section %	Number of damage nuclei	Area of crack on half the net section %	Number of damage nuclei
16101	No heating applied	3.11		46	9	13	31
16105		2.80		52	19	7	20
16109		2.47		42	35	40	37
16115		2.02		44	15	22	23
16119		2.23		58	16	31	37
16103	0	0.454	15.7	51	34	42	23
16113	0	0.446	19.2	46	38	41	44
16108	19.7	0.963	37.1	47	39	45	41
16107	40	1.34	50.4	54	28	40	26
16116	40	1.25	57.3	45	39	37	24
16102	60	2.01	67.9	46	23	44	20
16106	60	1.61	59.6*	54	30	46	41
16112	60	1.58	66.5	48	27	45	33
16104	80	2.43	85.7	55	33	52	26
16117	80	1.76	82.2	49	29	30	21

* Failed before application of heat.

† 1st digit denotes material, 2nd and 3rd digits identify the bar, 4th and 5th digits identify position in the bar from leading edge of extrusion.

Table 4

FATIGUE TESTS WITH ONE APPLICATION OF HEAT (BAR 39)

1000 HOURS AT 150°C AT 18000 lb/in^2 TENSION

Specimen number	% of nominal endurance at which heat was applied P	Actual endurance 10^6 cycles	$\frac{\text{Actual endurance}}{\text{Nominal endurance}}$ %	Major fatigue crack		Minor fatigue crack	
				Area of crack on half the net section %	Number of damage nuclei	Area of crack on half the net section %	Number of damage nuclei
13901	No heating applied	2.12		61	24	48	25
13905		2.27		63	30	46	24
13910		3.63		56	24	56	24
13915		2.47		51	24	45	23
13919		1.55		56	24	53	25
13903	0	0.453	18.0	44	26	42	24
13911	0	0.616	26.9	57	31	46	23
13907	19.8	0.913	38.0	41	30	37	24
13914	20	0.858	38.7	66	19	43	31
13909	40	1.28	54.9	47	25	44	22
13918	40	1.22	57.8	48	22	44	22
13906	60	1.64	67.4	46	25	43	29
13912	60	1.64	72.4	47	26	46	24
13902	80	2.13	83.8	49	25	44	21
13904	80	1.52	61.8*	52	25	47	26
13917	80	1.84	85.8	47	25	46	27

* Failed before application of heat.

Table 5

FATIGUE TESTS WITH ONE APPLICATION OF HEAT (BAR 76)

1000 HOURS AT 150°C AT 18000 lb/in^2 COMPRESSION

Specimen number	% of nominal endurance at which heat was applied P	Actual endurance 10^6 cycles	$\frac{\text{Actual endurance}}{\text{Nominal endurance}}$ %	Major fatigue crack		Minor fatigue crack	
				Area of crack on half the net section %	Number of damage nuclei	Area of crack on half the net section %	Number of damage nuclei
17601	No heating applied	1.87		51	30	45	31
17605		2.49		58	30	39	34
17611		2.65		45	20	37	24
17615		1.45		45	32	41	40
17619		1.30		42	47	38	38
17603	0	0.461	20.3	45	34	36	46
17613	0	0.600	34.4	52	41	45	44
17616	40	1.13	69.8	49	37	44	42
17612	60	1.41	78.6	50	36	41	31
17618	60	1.10	71.6	53	28	39	39
17604	80	2.18	99.1	43	38	40	37

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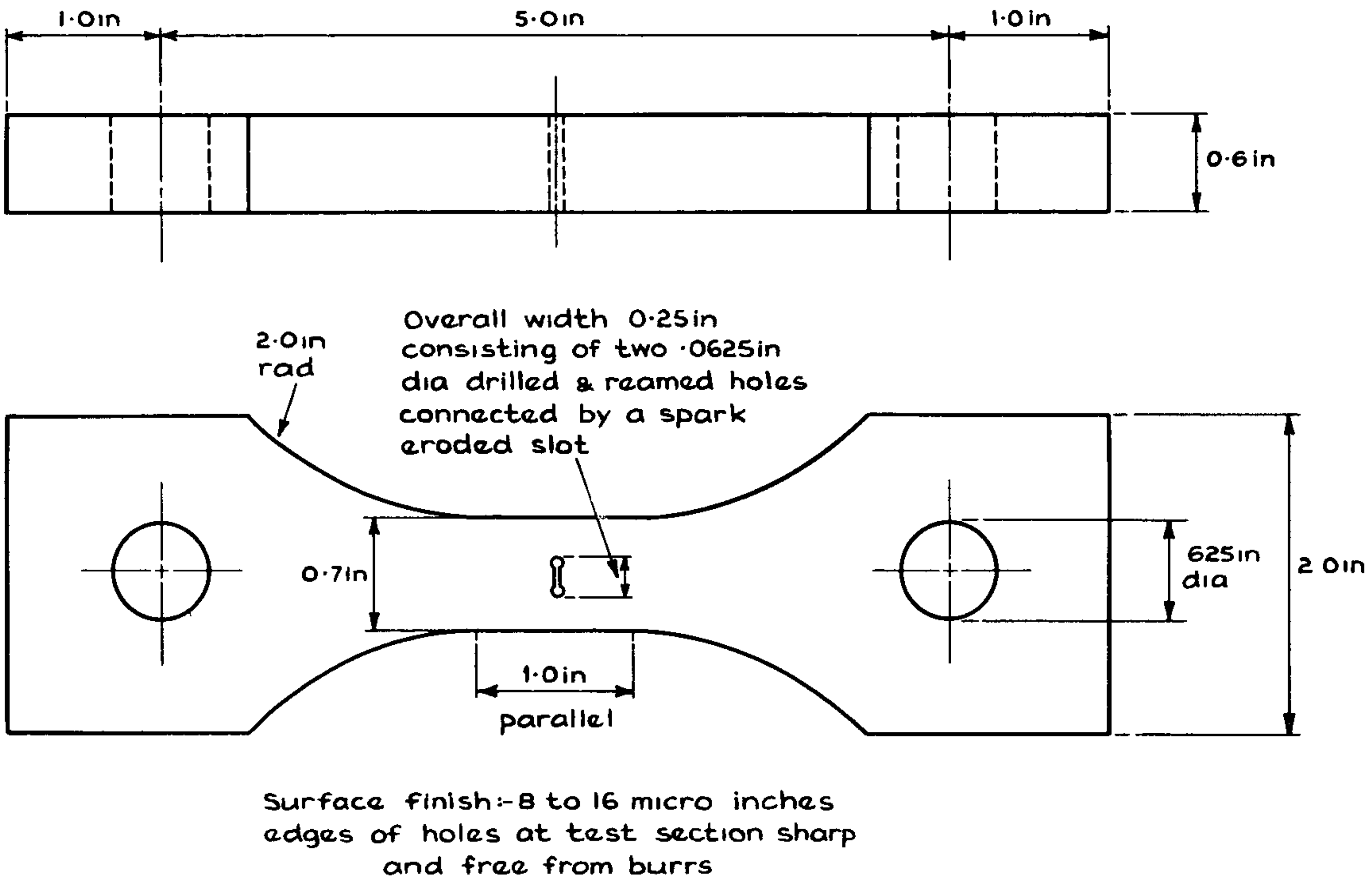


Fig.1 Notched specimen - net stress concentration 3·4

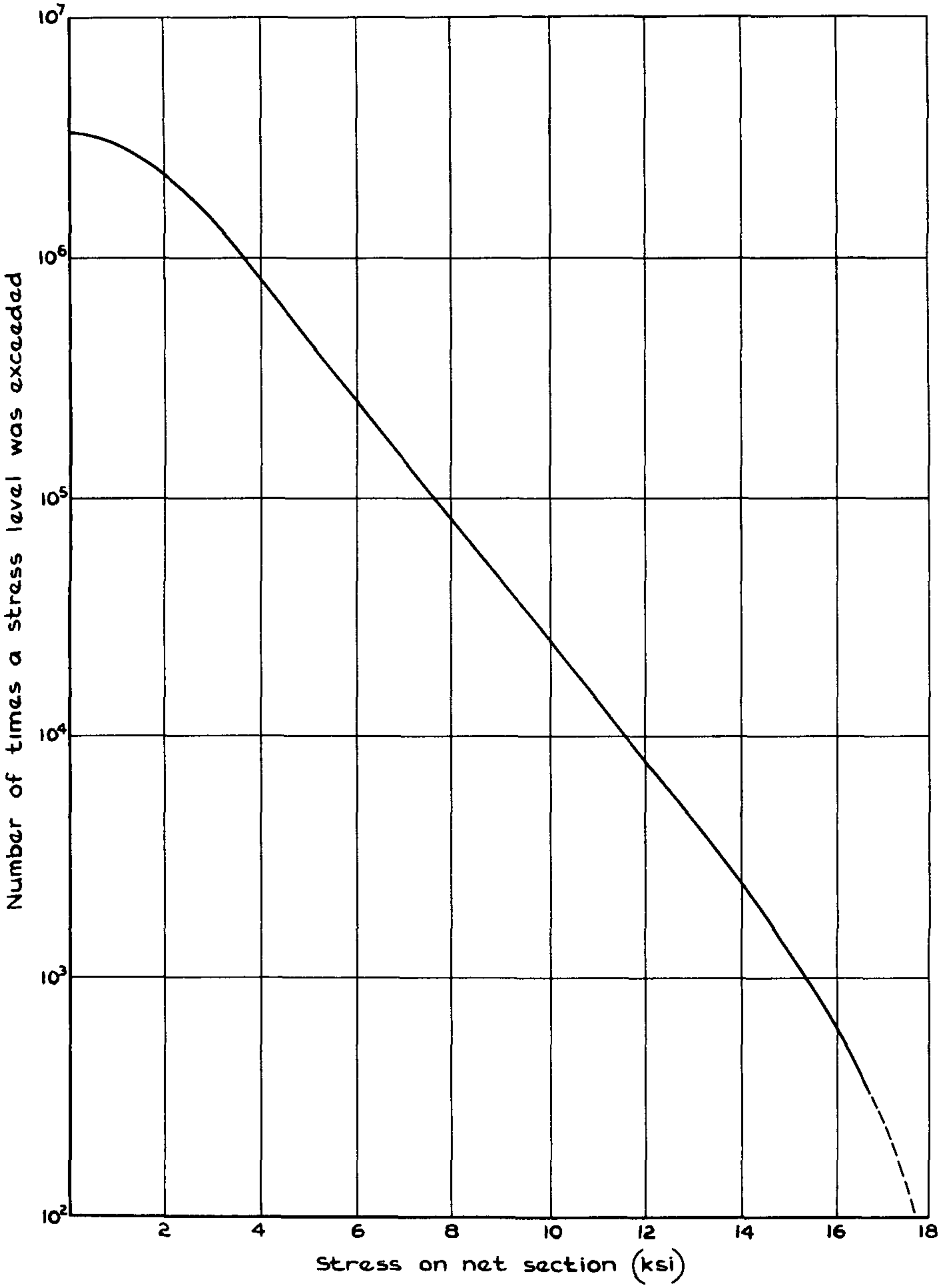
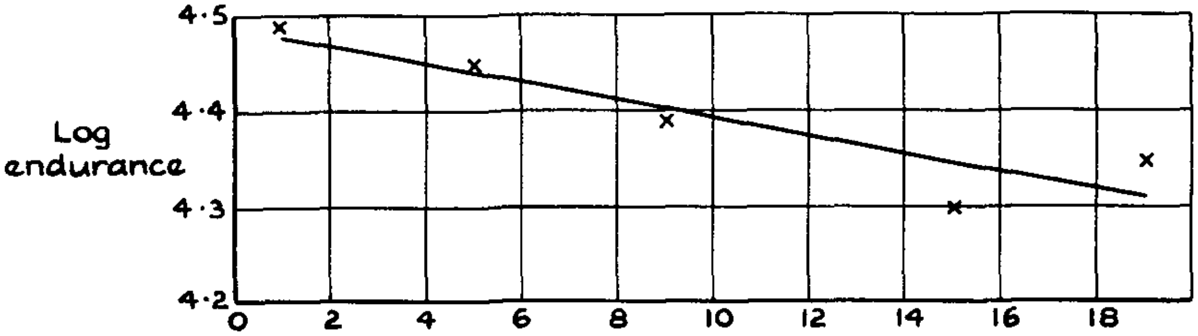
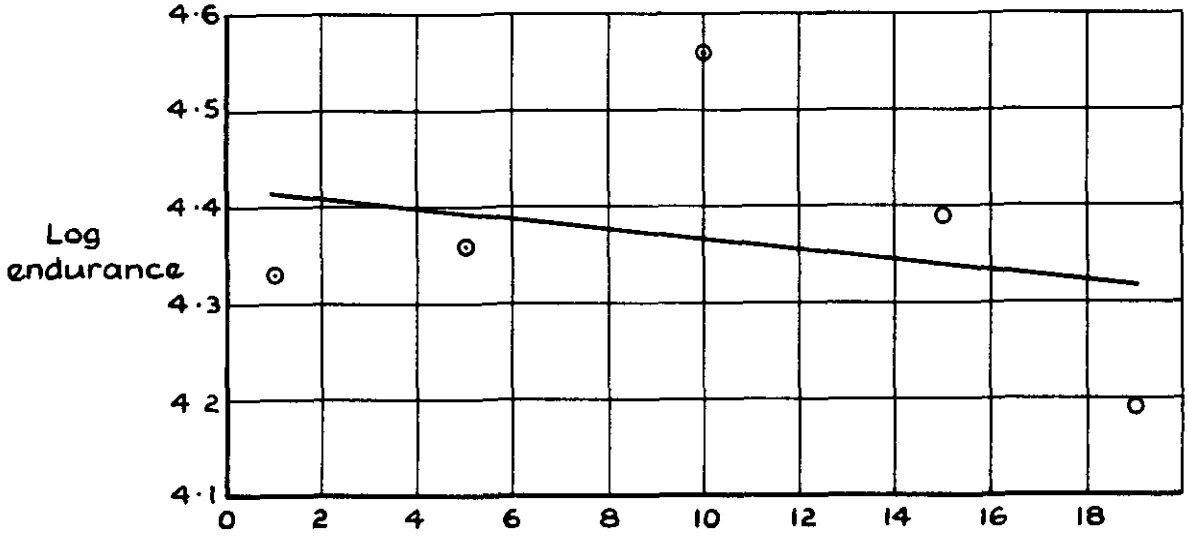


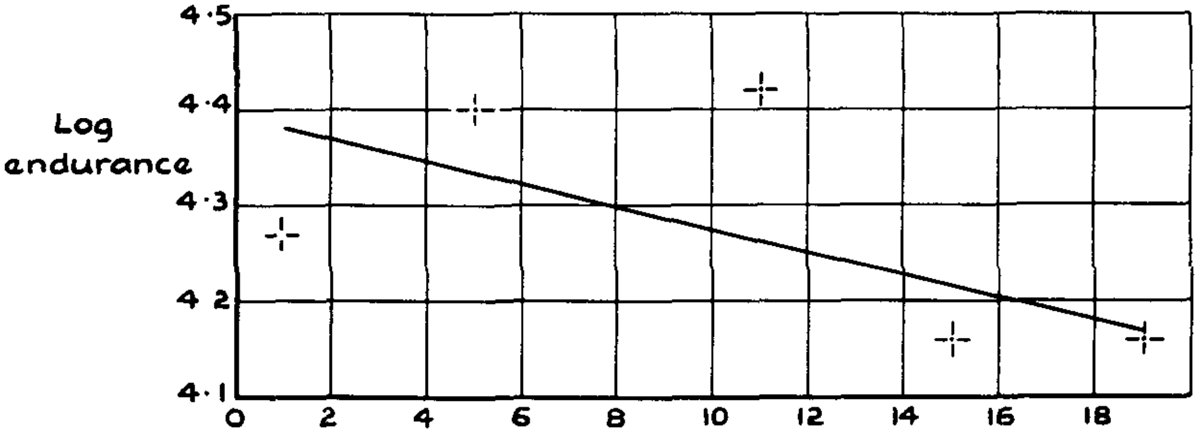
Fig. 2 Sample of stress spectrum



Position of specimen in bar 61

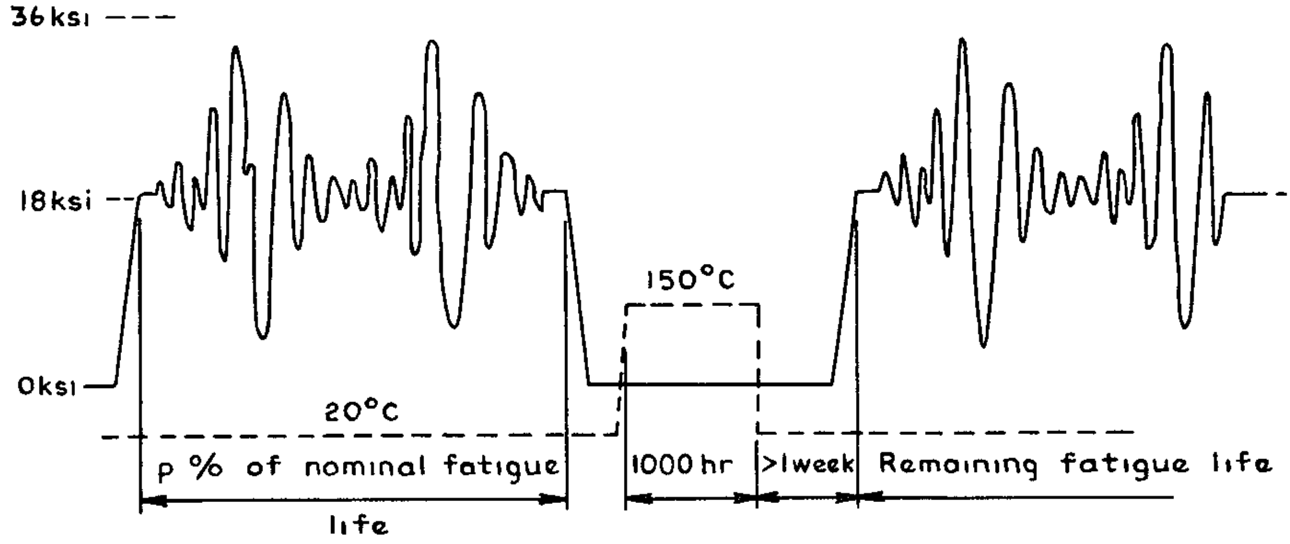


Position of specimen in bar 39

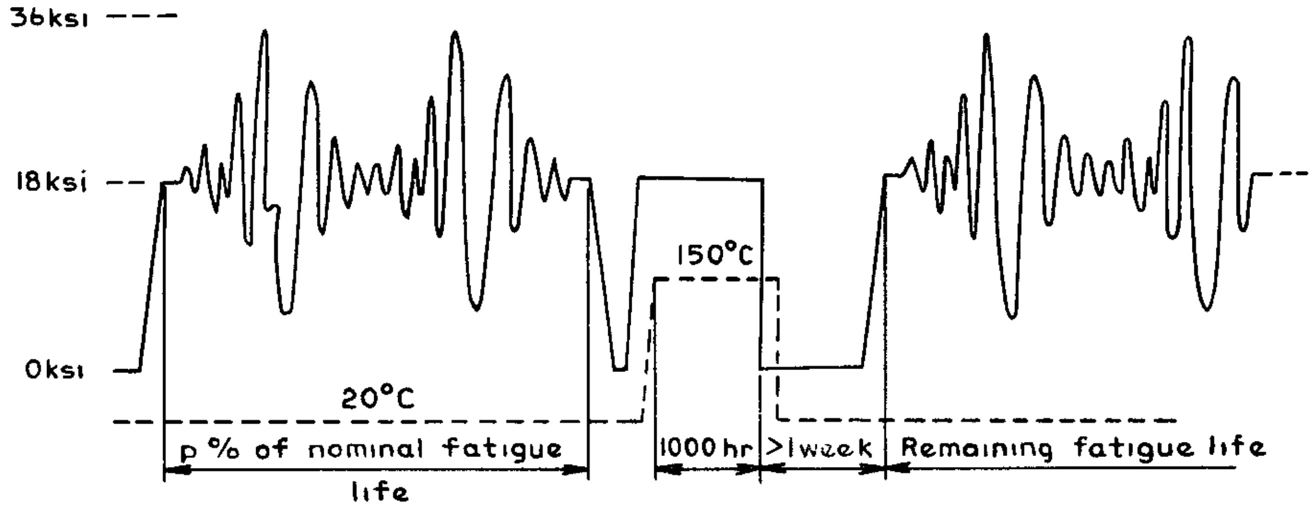


Position of specimen in bar 76

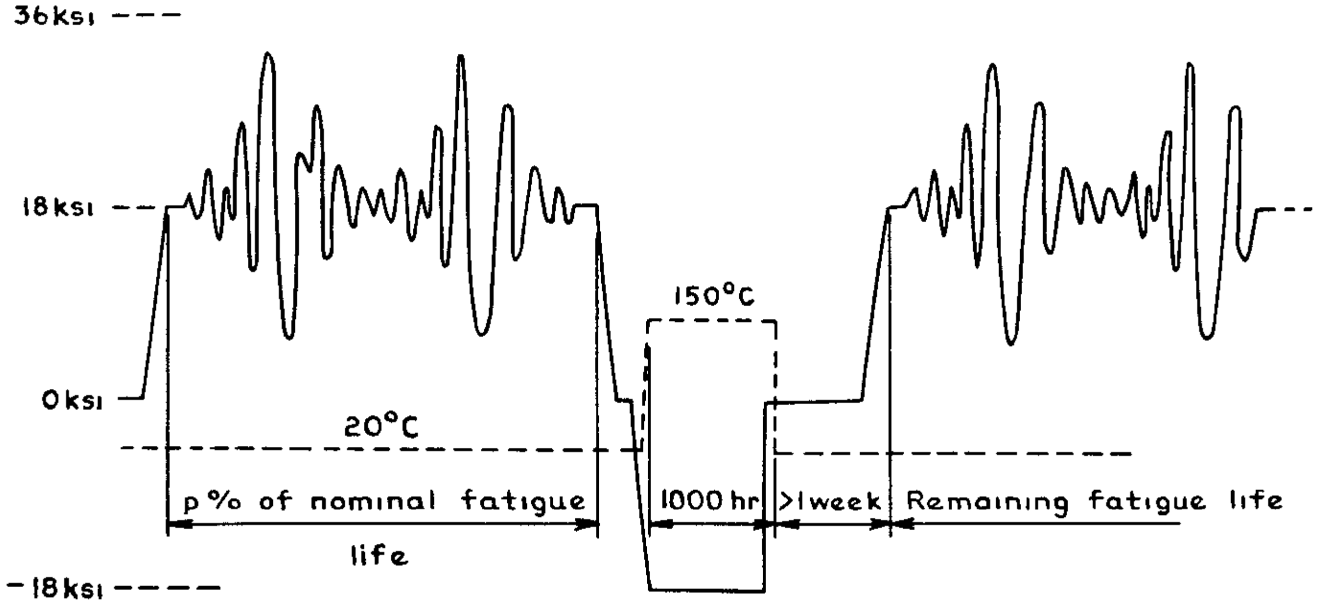
Fig. 3 Variation in fatigue endurance along bars of material



a Heat at zero stress

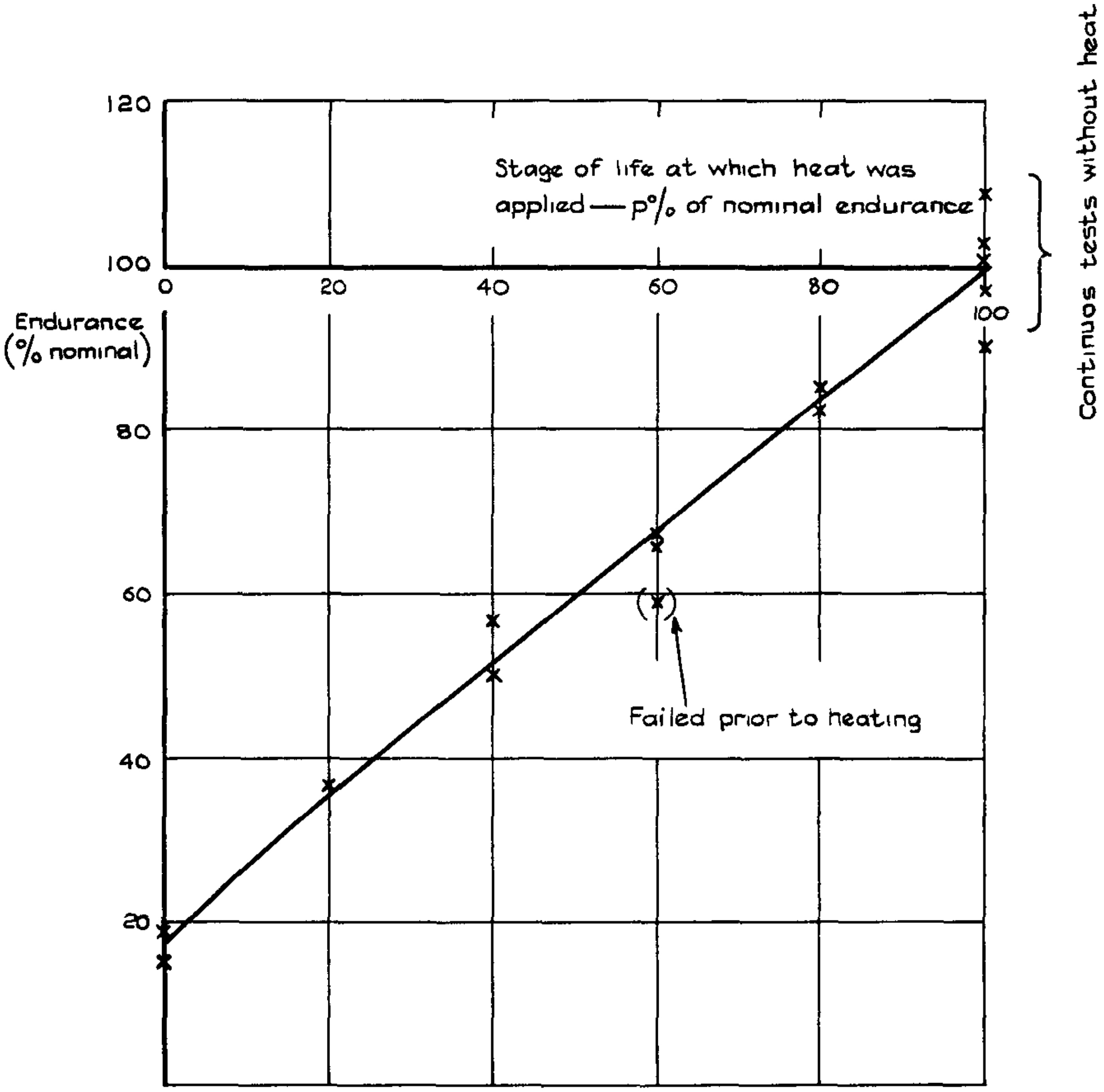


b Heat at 18ksi tension



c Heat at 18ksi compression

Fig.4 Stress-temperature sequences used



RR 58, $K_t = 3{\cdot}4$, thick section
Fatigue mean stress 18ksi net
Random gust spectrum 3ksi rms
Nominal endurance about 2×10^6 cycles
Heat 1000 hours at 150°C at zero stress

Fig. 5 Variation in endurance with stage of life at which heat was applied at zero stress (bar 61)

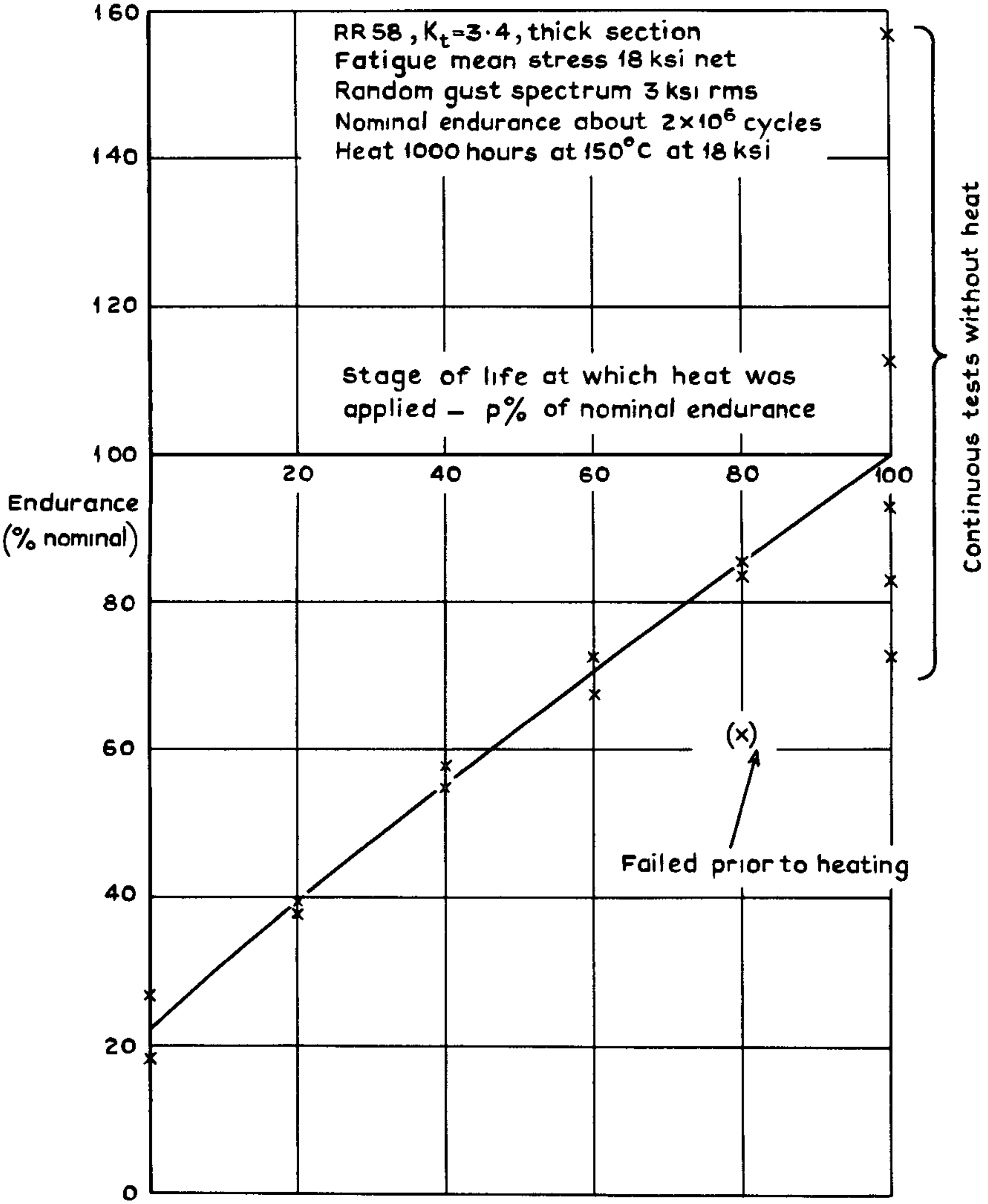


Fig.6 Variation in endurance with stage of life at which heat was applied at 18 ksi tension (bar 39)

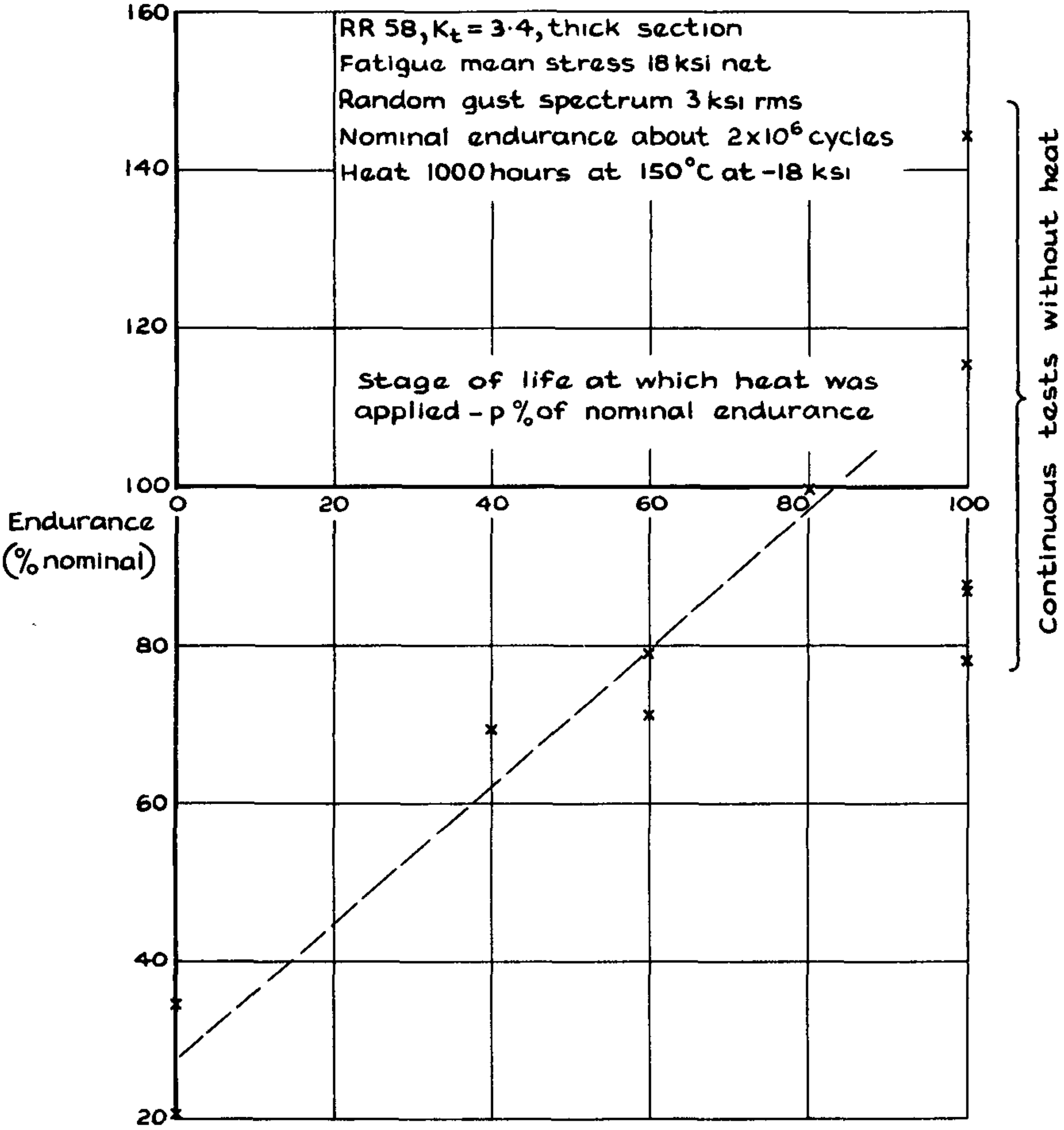


Fig.7 Variation in endurance with stage of life at which heat was applied at 18 ksi compression (bar 76)

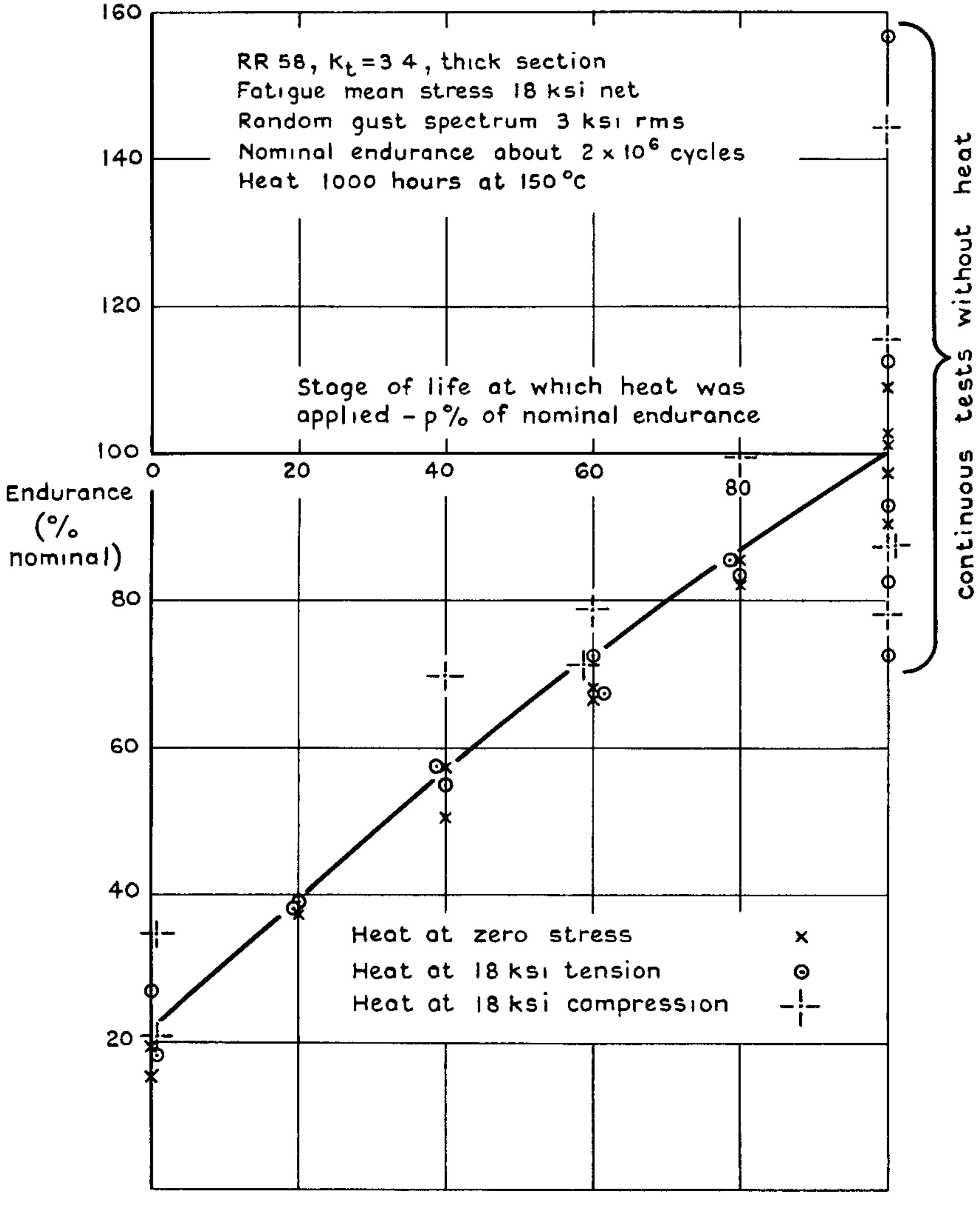


Fig.8 Variation in endurance with stage of life at which heat was applied – general trend

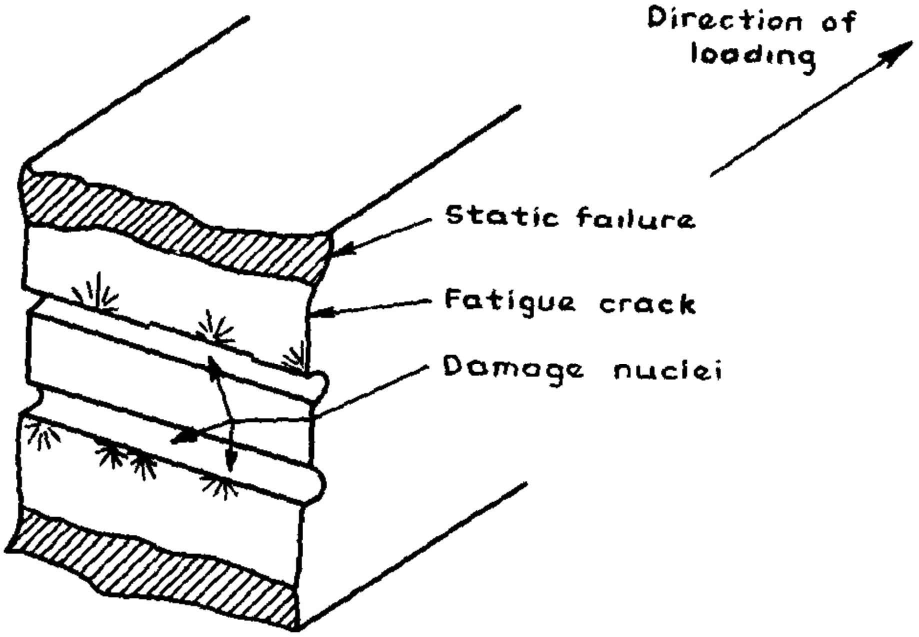


Fig.9 Fracture surface of notched specimen showing nuclei in the bore of the notch

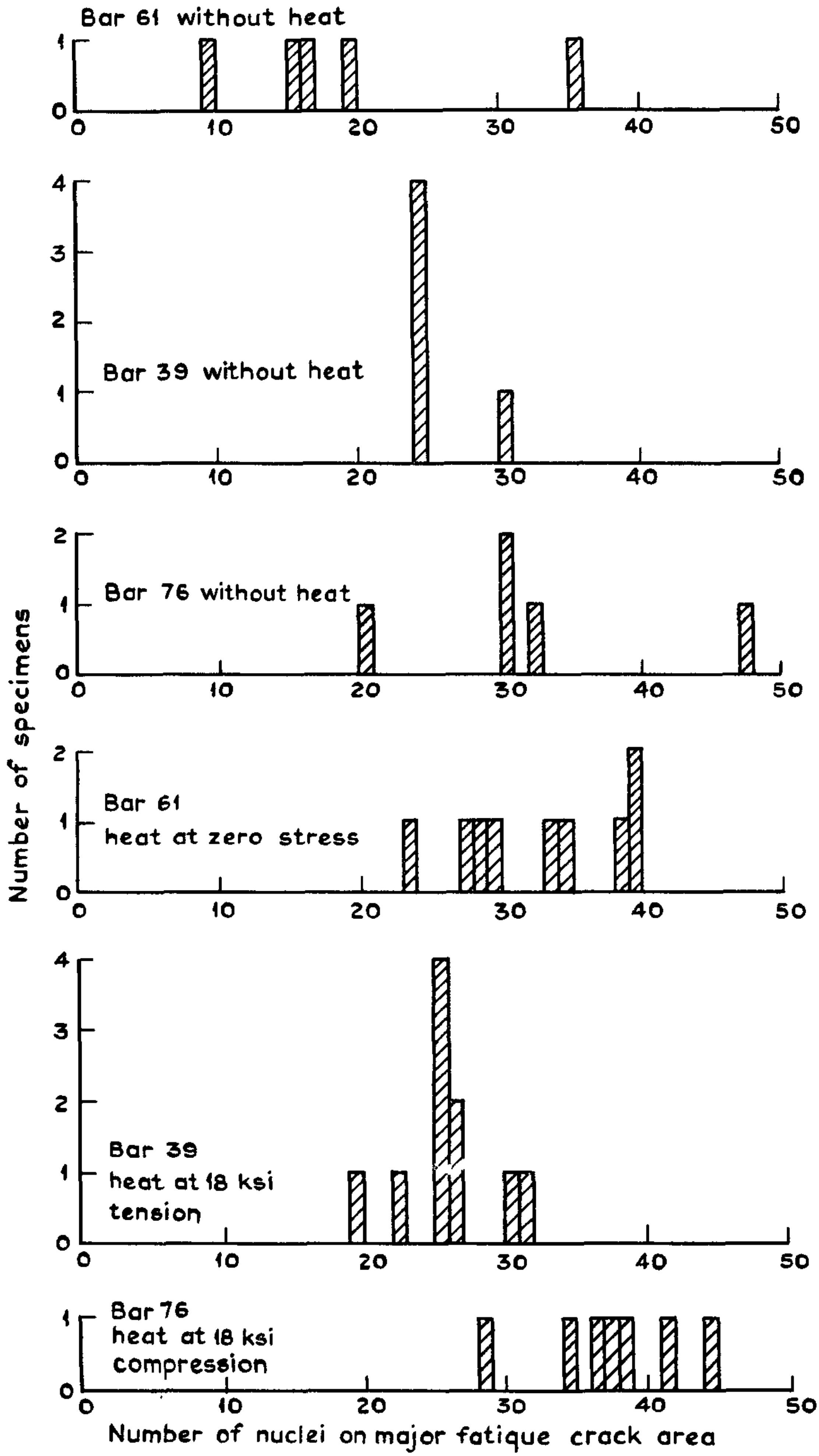
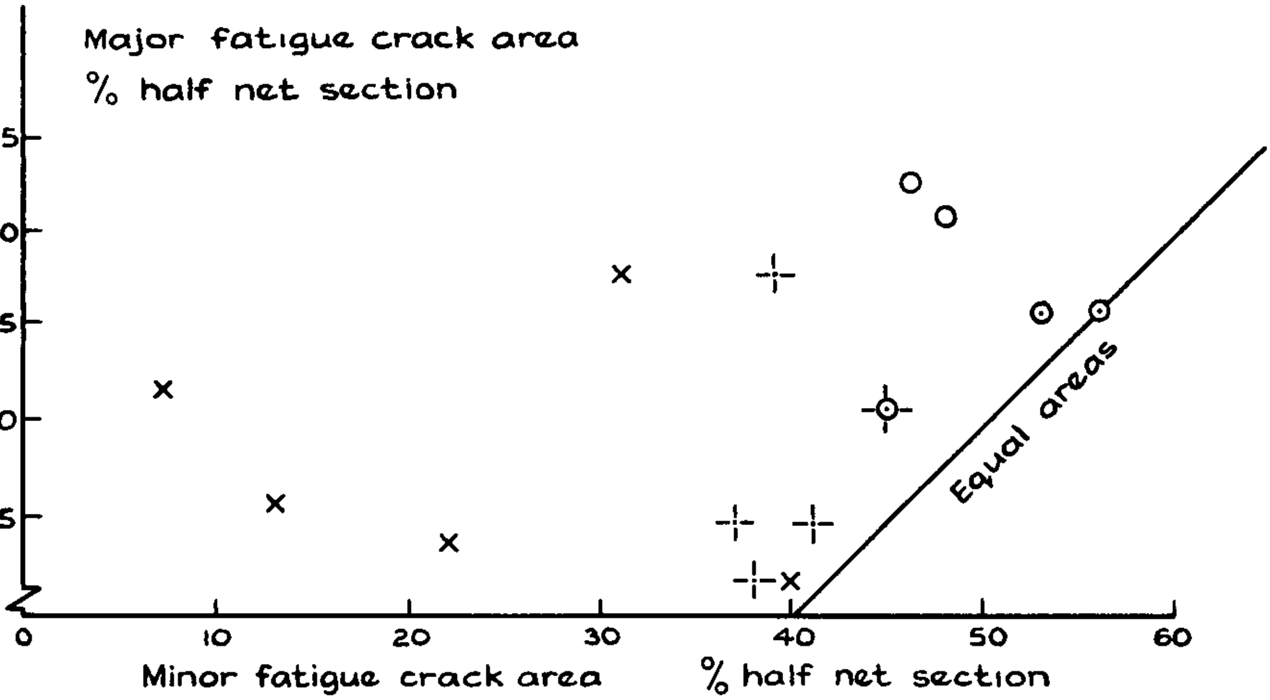
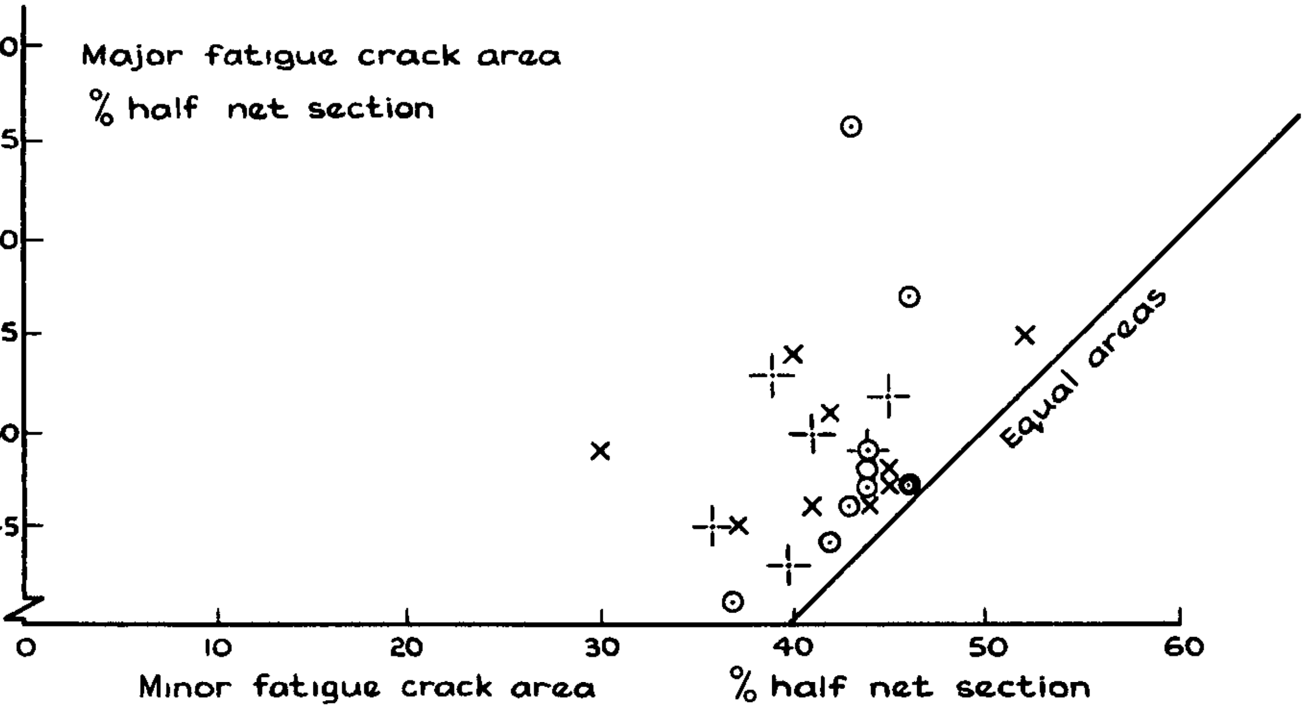


Fig. 10 Frequency with which numbers of nuclei occurred



a Tests without heat



b Tests with heat

Fig.11a&b Comparison of major and minor fatigue crack areas

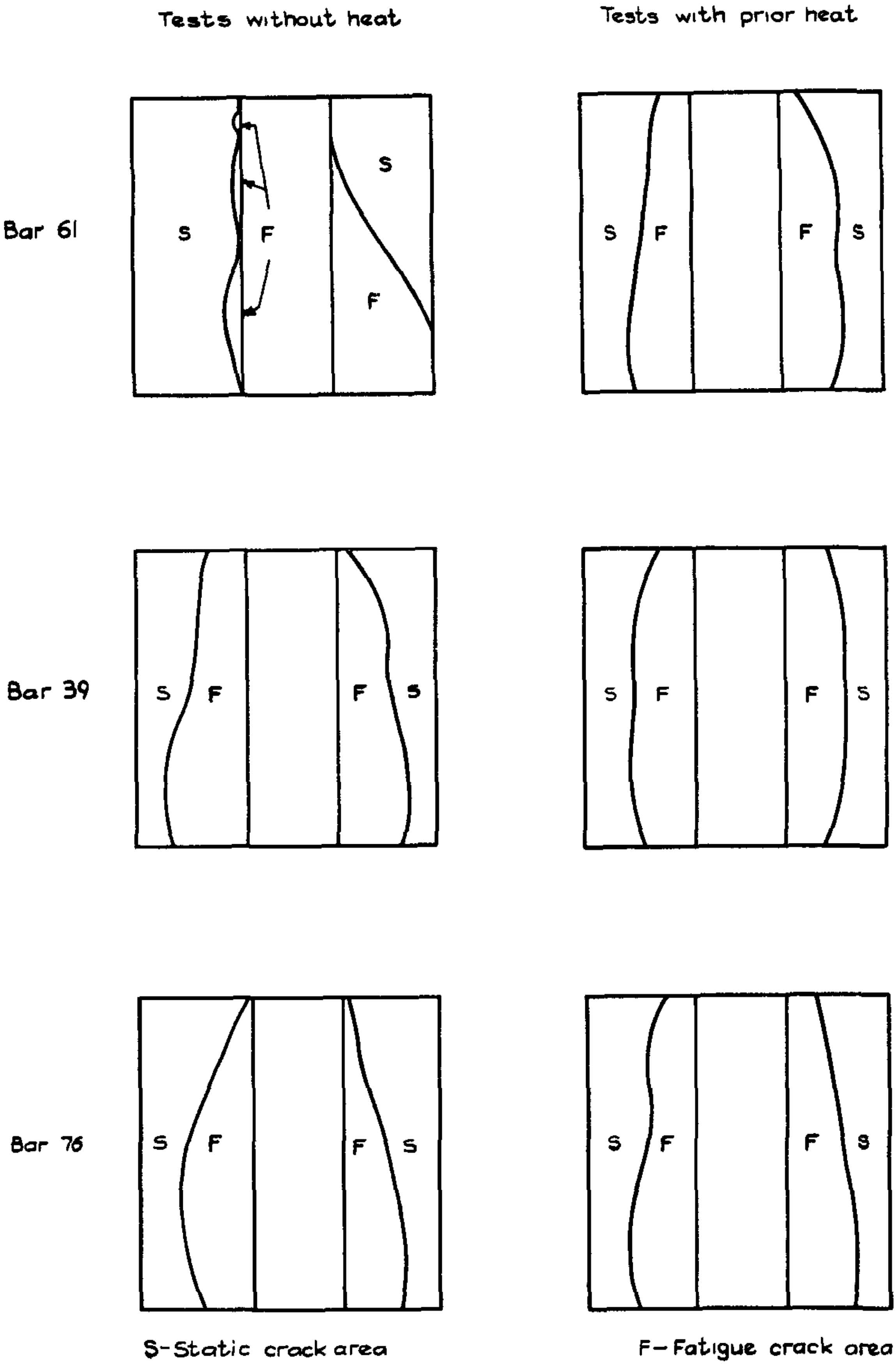
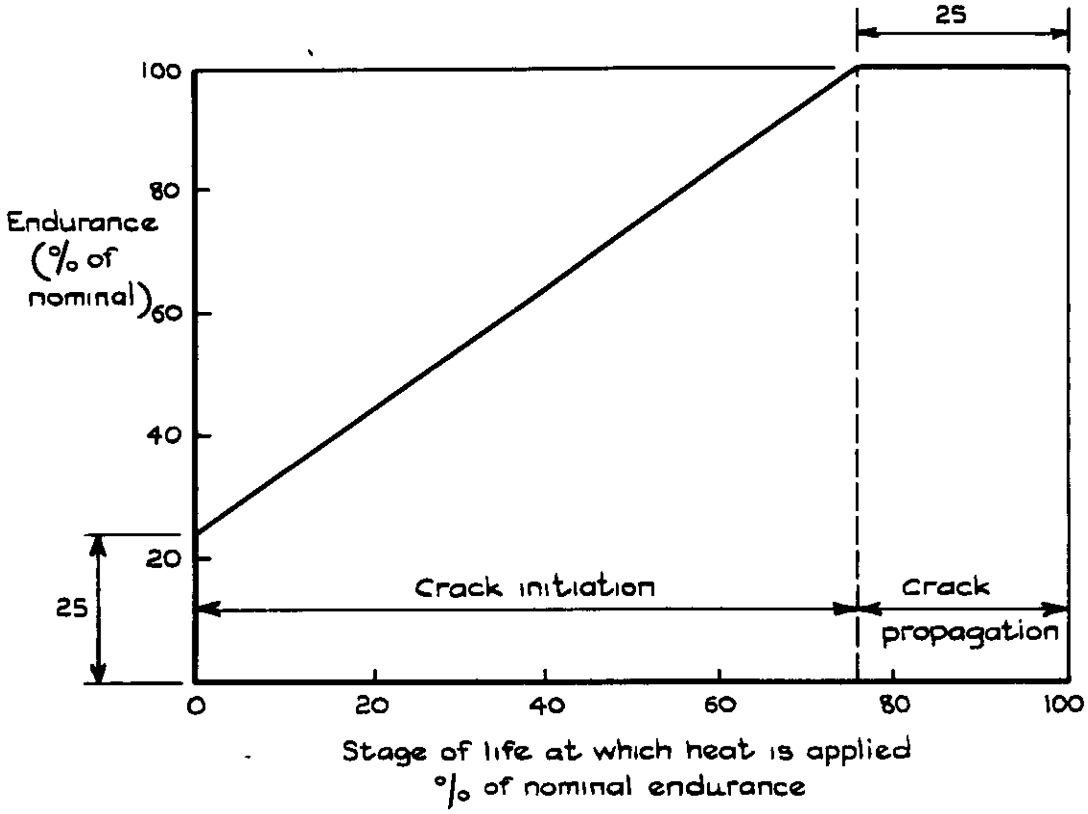
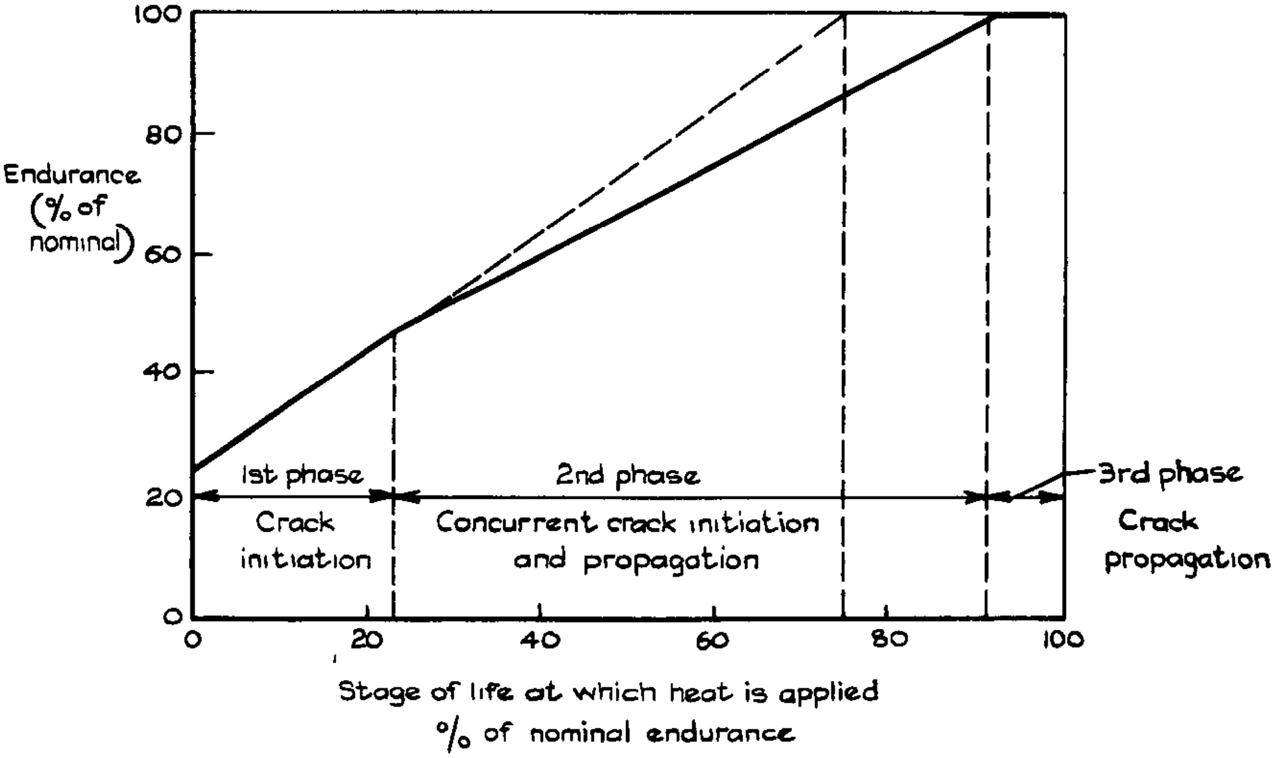


Fig.12 Typical examples of fatigue crack shape



a Consecutive crack initiation and propagation



b Concurrent crack initiation and propagation

Fig.13a&b Diagrams of hypothetical fatigue–heat interaction

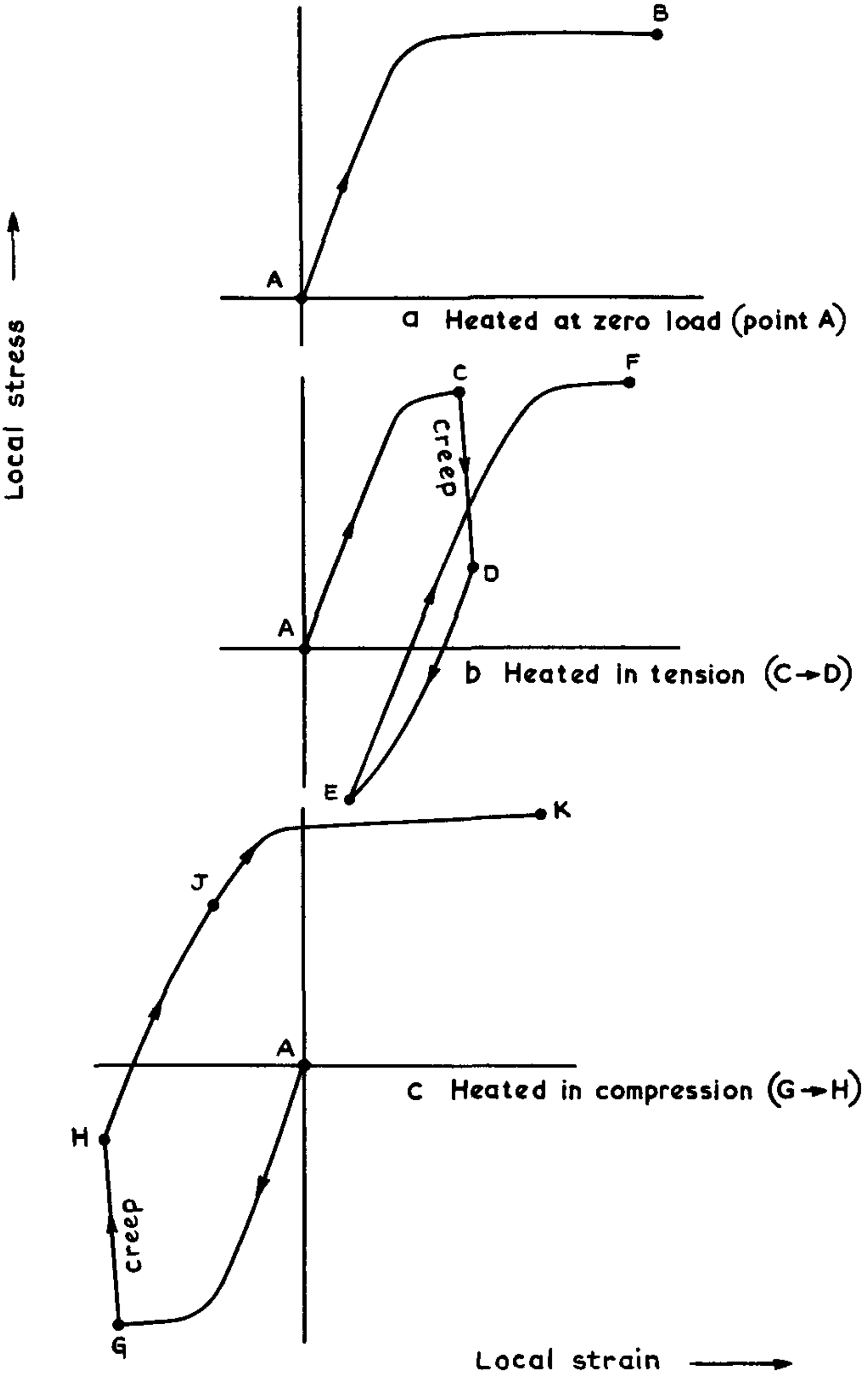


Fig. 14 Variation of local stress at the notch due to heating (a) At zero load, (b) In tension, and (c) In compression, followed by the application of a large tension

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Fatigue tests were made on notched specimens of DTD 5014 (RR58) in fluctuating tension of randomly varying amplitude representing a gust load spectrum The application of heat for 1000 hours at 150°C at any stage of the fatigue life reduced the remaining life to 25% of expectation and markedly reduced the scatter in life The effect, which was similar whether the load during heating was zero, tension or compression, is attributed to the rapid initiation of cracking following a period of heating due to loss of work-hardening at the surface of the notch

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