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AN EXPERIMENTAL STUDY OF THE STRESS HISTORIES AT STRESS CONCENTRATIONS IN ALUMINIUM ALLOY SPECIMENS UNDER VARIABLE AMPLITUDE LOADING SEQUENCES

by

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SUMMARY

In this paper an investigation is described of residual stresses associated with plastic deformation at a stress concentration in an aluminium alloy specimen. Local stresses were determined, by an indirect method, under a variety of sequences of loads which included peaks high enough to cause local yielding. Sequences at both zero and a positive mean stress were applied. Conclusions are drawn with respect to the effects of residual stresses generated by such yielding on the accuracy of fatigue life prediction and on the design of loading sequences to be applied in the laboratory as a representation of service loading actions.

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CONTENTS

Conversions 1 ksi = 1000 $lb(f)in^{-2}$ = 6.894 MNm^{-2} = 0.689 Hb

1 INTRODUCTION

It is generally accepted that certain aspects of the fatigue behaviour of notched aluminium alloy components can be explained by residual stresses generated at the point of fatigue initiation by local yielding under high loads in either direction[1]. Several cases in which particular fatigue behaviour has been attributed to such residual stresses are of practical interest. For example there is the extension or reduction of fatigue life by the application of a single unidirectional load, tensile or compressive, at the beginning of the fatigue life. Also there is the fact that the application of Miner's Rule tends to result in an underestimate of life when used to calculate the fatigue lives of aluminium alloy notched components which are subjected to a symmetrical variable amplitude loading about a positive mean stress. Again, residual stresses provide an explanation for some differences in life which have been found when the order of application of the loads has been changed in block programme fatigue tests. Finally, and perhaps of greatest interest, residual stresses induced by air-ground-air cycles in aircraft load histories can accentuate fatigue damage under subsequent loading and can cause Miner's Rule to overestimate fatigue life.

It is of some importance to quantify the values of residual stress which may occur under the wide range of loading conditions encountered in practice - both in service and in laboratory simulation of service loads. A knowledge of the values will enable estimates to be made of the consequent effects on the fatigue life.

In this paper a programme of work is described in which local stresses at a stress concentration were determined under a variety of sequences of loads which included peaks high enough to cause local plastic deformation. Variable amplitude load sequences at both zero and a positive mean stress were applied to notched 2L65 aluminium alloy specimens with a stress concentration factor of 2.27. During these tests the strain histories at the notch root were measured. Since some plastic deformation occurred at the stress concentration, there was no simple relationship between stress and strain in the material affected. Therefore, in order to determine the associated stress histories, plain specimens were subsequently subjected to the same strain histories as those previously measured at the notch. The stress histories which had to be applied to the plain specimens, in order to produce the required strain histories, were then measured. This information gave a good approximation[2,3] to the axial stress histories at the notch root and from this information the residual stress histories were calculated. Conclusions are drawn with respect to the effects of residual stresses on the accuracy of fatigue life prediction and on the specification of loading sequences to be applied in the laboratory as a representation of service loading actions.

2 SPECIMENS AND MATERIAL

The specimens were made in BS2L65 material - all of the specimens were cut from a single bar measuring 3.375 in × 1.0 in × 12 ft. Dimensions of the notched and plain specimens are shown in Figs.1 and 2. (For the notched specimens the stress concentration factor was 2.27.) Strain gauges having a gauge length of 0.0625 in were bonded to the specimens as shown.

3 TEST EQUIPMENT

The specimens, both notched and plain, were loaded in a 20 ton electro-hydraulic fatigue machine (Fig.3) through wedge grips. Schematic diagrams of the equipment are shown in Fig.4. Loads were controlled by hand through a potentiometer which supplied the required variable dc voltage to the machine input. For both types of specimen a pair of strain gauges (gauges 1 and 2 in Figs.1 and 2) was wired into an electronic strain gauge meter. Continuous load vs. strain histories were recorded throughout the tests by connecting the output of the strain gauge meter to the X axis of an X-Y recorder and the output of the load cell of the machine to the Y axis. As can be seen from Fig.4 a force feedback system was used throughout for load control of the electrohydraulic machine.

4 TEST PROCEDURE

The notched specimens were subjected to one of two predetermined loading sequences (Fig.5) - Sequence 1 was at zero mean stress and Sequence 2 was at a positive mean stress. During the tests the X-Y plotter recorded the histories of load, which was directly proportional to net stress, vs. local strain as measured at the strain gauges (1 and 2 - Fig.1). The second set of strain gauges (3 and 4 - Fig.1) was normally used as a check on the reading of the first set at each extreme load value, but continuous readings were taken on this second set in the event of a failure on the first set.

From the notched specimen test results a table was compiled, for both sequences, of the local strain value for each net stress maximum and minimum. Plain specimens were then subjected to the same strain histories of maxima and minima, and stress vs. strain histories were recorded as before. The stress vs. strain diagrams obtained from both types of specimen are given in Figs.6-21. These diagrams are derived from the results of at least two tests except for the notched specimen results of half cycles 31-36 in Sequence 1.

Since the loads were controlled manually, the frequency of application of the loads varied somewhat from specimen to specimen and from cycle to cycle. In general, one half cycle was applied in about forty seconds.

5 ACCURACY

It is considered that the loading accuracy of the machine and the accuracy of the strain gauge meter in recording resistance changes in the strain gauges were both within 2% of the true value.

Strain gauges can experience a dc drift and change in gauge factor under cyclic loading, particularly at large alternating strains and this was a critical consideration in the foregoing tests. In the context of this Report, dc drift and change in gauge factor are only of importance insofar as they varied from notched specimen to plain specimen, since it was the object here to determine accurate local stress histories on the plain specimen by reproducing the recorded local strain histories from the notched specimen. Absolute accuracy was therefore unnecessary. For the notched specimen sequences the maximum difference in strain recorded between any two specimens under nominally identical loading conditions, or between any two sets of gauges on the same specimen, was 800 microstrain at the end of Sequence 2. This value represented only about 5% of the maximum strain applied. It was concluded that the repeatability of the strain gauges was satisfactory.

At the time this work was carried out it was not possible to use other than force feedback to control the loads on the electrohydraulic fatigue machine. The result of this was that control of strain values was difficult when gross yielding occurred in the plain specimens. However, in cases where slight overstraining occurred, it was found that as soon as yielding was induced, in subsequent cycles in the reverse direction the stress vs. strain sequence became indistinguishable from those of other specimens which had not been overstrained. The sequences shown here have been idealised to give the best of at least two tests in every case. Clearly strain or displacement feedback can ensure more accurate control in future experiments.

6 RESULTS

Net stress on notched specimens vs. local strain histories are given in Figs.6-14 (even numbers) for Sequence 1 and in Figs.16-20 (even numbers) for Sequence 2. Plain specimen results are given in Figs.7-15 (odd numbers) for Sequence 1 and in Figs.17-21 (odd numbers) for Sequence 2. The results of the investigation are summarised in Figs.22-24 in which net stress, local stress, local strain, and residual stress vs. time are plotted. For convenience in plotting these diagrams the net stress vs. time waveform is shown as sinusoidal with each half cycle taking the same time regardless of amplitude - all the other histories are constructed with reference to this assumed stress waveform. In practice this was not so since the applied loads were controlled manually (see section 4). However this is not likely to significantly affect the shape of the stress vs. strain diagrams. Also the local strain values are strain gauge readings which show some dc drift as discussed in the last section. Finally, it is important to note the definition of residual stress as plotted here. The residual stress is defined as that axial stress which would be left at the root of the notch if the net stress were removed and the specimen then behaved elastically. Therefore:

$$\text{Residual stress} = \text{local stress} - K_t \times \text{net stress}$$

This value only changes when any local yielding occurs at the notch root.

7 DISCUSSION

The sequences of loads used in this work were devised so as to try to obtain a broad picture of the way that residual stresses can be affected by loading sequence, and can themselves affect cumulative damage behaviour. For this reason varied loading patterns were employed. In this section the stress and strain relationships over the first few cycles of Sequence 1 are discussed in some detail with a view to familiarising the reader with the diagrams. The remaining discussion is not so detailed and is concerned mainly with probable effects on fatigue behaviour of the observed stress vs. strain relationships. It is hoped that particular aspects of behaviour revealed in this work will be studied more closely in future programmes.

7.1 Sequence 1 - zero mean stress

In this sequence the main emphasis is on the effect of a high unidirectional load - how it can affect the fatigue behaviour of a component under subsequent low level cycling by generating residual stresses, and how the effects of such stresses are modified by the subsequent loading history. Fig.5 shows the sequence of net loads for Sequence 1.

Consider half cycles 1-6. Fig.6 shows the net stress vs. local strain history for the notched specimen. The corresponding net stress vs. time history is shown as an insert. On the large diagram half cycle 1 starts at the origin and the stress vs. strain curve is linear up to point A, indicating elastic behaviour. Between A and B the non-linearity shows that yielding occurred locally at the notch. On commencing unloading at B the material behaved elastically down to approximately point C after which a very small amount of reverse (compressive) yielding occurred between C and D. Thus at D at the end of half cycle 1, the material at the notch root was experiencing a strain of 3200 microstrain. On half cycle 2 yielding continued between D and E. After reaching the negative peak at point E, it can be seen that the material behaved in virtually an equal but opposite fashion to that which occurred after the positive peak of half cycle 1, with yielding occurring in this case at approximately point F and with a strain value of -3500 microstrain being left at point G at the end of half cycle 2. On the next half cycle yielding occurred up to the peak at point H and it can be seen from the diagram that over the next three-quarters of a cycle no detectable yielding occurred so that on the stress vs. strain diagram points H, J, K and L all lie on the same straight line with the plot reversing at point K and returning up the same line. The strain values at the end of half cycles 3 and 4, points J and L respectively, were therefore the same and equal to -2400 microstrain. On half cycle 5 the material behaved elastically up to point M coincident with point H and then continued on a path of progressive yielding between M and N. Subsequently on half cycles 5 and 6 the specimen behaved in a manner similar to that which occurred on half cycles 1 and 2, finishing at point R which was virtually coincident with point G. Fig.22b gives the local strain vs. time waveform which, for half cycles 1-6, was obtained by projecting the net stress vs. time waveform (shown in Fig.22a) for the appropriate half cycles along the stress axis of Fig.6 and reading corresponding local strain values. Points A to R are shown.

Turning now to Fig.7 it will be remembered that this diagram shows the stress vs. strain history for a plain specimen subjected to the same strain history as measured at the root of the notched specimen, and so the plain specimen experienced virtually the same axial stress history as the material at the root of the notch. Therefore in order to obtain the local stress at the notch root corresponding to any point on Fig.6, then the strain value should be read from Fig.6 and the local stress value will be given by the corresponding point on Fig.7 having that strain value. For example it can be seen from Fig.7 that point D which was previously shown to have a strain value of 3200 microstrain is also associated with a compressive stress value of 29 ksi.

Fig.7 can be seen to be similar in form to Fig.6 but yielding appears more prominently than on the previous figure. For instance it can seen that some yielding occurred on half cycle 4 between points J and K, whereas this was not large enough to be apparent on Fig.6. Also the position of point C, after which slight yielding occurred, was not clear from Fig.6 alone. However, in general the stress vs. strain curves for plain specimens can be followed around in the same manner as those for the notched specimens.

Fig.22c shows the local stress vs. time waveform which, for half cycles 1 to 6, was obtained by projecting the local strain waveform (shown in Fig.22b) for the appropriate half cycles along the strain axis of Fig.7 and reading corresponding points along the stress axis. Points A to R are shown.

At the end of section 6 the quantity 'residual stress' was defined, and Fig.22d shows this as a function of time. Since the residual stress does not change unless any local yielding occurs and its value is assumed to be zero at the start of the tests, then it did not start to change until point A was reached. It then became more and more negative until the net stress peak was reached at point B whereupon no further change occurred until point C was reached after which some slight reverse yielding took place up to point D. Since the residual stress is defined as that stress which is left in the notched specimen if the specimen is unloaded elastically to zero net stress, then whenever the stress vs. strain curves cross the strain axis in Fig.6 then the corresponding stress value obtained from Fig.7 is the residual stress, as well as being the local stress, at that point. Therefore the local stress at point D, which was previously shown to be 29 ksi compressive is also the residual stress at that point. From Fig.22d it can be seen that as was stated in section 6 the residual stress only changed whenever local yielding took place so that, for instance, the residual stress was constant between points H and M. Examination of Figs.22a to 22c makes the general point that where local yielding occurs at a notch root the local stress and net stress waveforms do not bear a simple relationship to each other. In Figs.22 to 24 the net stress, local strain, local stress and residual stress histories are shown for all the load sequences used in this programme.

In the following discussion the complete set of results is examined. Particular reference is made to the probable effects on fatigue behaviour of the observed changes in stress and strain state. The effect of half cycle 1 (net peak tensile load value $+P_3$) was to leave a state of stress and strain at the notch root given by point D on Fig.7. Similarly, after half cycle 2 (net peak compressive load value $-P_3$) the state of the material was represented by point G, approximately equal and opposite stresses and strains to point D. It can be seen from Figs.7 and 22d that the effect of the first quarter of a subsequent complete cycle of net stress of amplitude P_1 was to reduce the residual stress to about two-thirds of its value at G by yielding along GH. Then whilst the next three-quarters of a cycle HJKL was being applied virtually no further yielding occurred so the residual stress and strain values were approximately constant. It can be deduced that any further cycling at amplitude P_1 would have caused the stresses at the notch root to continue cycling approximately along HJKL. Therefore any fatigue damage at that level would be influenced by the raised local mean stress (equal to the residual stress in this case) given by points J and L. For this reason the rate of accumulation of fatigue damage would be greater than for a specimen which had not first been stressed by a compressive half cycle at level $-P_3$. However it should be noted that, as has been shown by Pattinson and Dugdale[4] for an aluminium alloy, local mean stresses can experience a slow cycle by cycle reduction under low level fatigue loading quite apart from any subsequent disruption of the residual stress field due to cracking. Therefore the increase in fatigue damage rate would not necessarily be expected to be permanent.

Half cycles 5 and 6 ($+P_3$, $-P_3$) were introduced to see whether subsequent cycling at level P_3 would follow the pattern established on the first two half cycles. As can be seen some differences were found (Figs.6 and 7) although the differences were not large, in line with the work of Hardrath and Crewes[3].

Half cycles 7, 8 and 9 (Figs.8, 9 and 22) had an applied net stress sequence similar to 2, 3 and 4 except for an overall change of sign, and it is notable that the variation in residual stress was virtually equal but opposite in the two cases.

Half cycles 1-9 therefore demonstrate how a notched aluminium alloy specimen can have its fatigue life at a low alternating stress level extended by a preceding tensile load and conversely reduced by a preceding compressive load. Also it can be deduced that if a block programme at zero mean stress were to be applied to the notched specimen, and if cycles of amplitude P_3 were to be succeeded by cycles of amplitude P_1 then the direction of the last half cycle of amplitude P_3 would be the most important factor in determining the state of residual stress under loading at the lower amplitude. The rate of accumulation of fatigue damage at the lower level (and hence the total life to failure) would then be affected by the residual stress. It can also be seen from half cycles 1-9 that due to the reduction in absolute value of the yield point in one direction after yielding in the opposite direction (Bauschinger effect), yielding is liable to occur during the first complete cycle of loads of any amplitude immediately following a high level half cycle which itself caused substantial yielding. Therefore the value of residual stress during low level cycling following a high load depends substantially on the low level alternating stress value as well as on the preceding high stress value.

Figs.8-11 show the stress vs. strain patterns obtained for net load sequences $-P_3$ $+P_1$ $-P_3$ and $+P_3$ $-P_1$ $+P_3$ (half cycles 10-15). These sequences were as in half cycles 2-5 and 7-10 intended to represent a load of value P_3 followed by an indeterminate number of half cycles of magnitude $\pm P_1$ and a final load of value P_3. In this case only one half cycle at level P_1 was applied in each sequence (half cycles 11 and 14) and it was assumed that any subsequent cycling at that level would follow paths similar to those of half cycles 3 and 4, and 8 and 9 (with some small cycle by cycle relaxation of residual stress value as suggested above). In contrast to the earlier sequences (half cycles 2-5 and 7-10) however, the final load in both sequences was in the same direction as the initial preload. A point to emerge from this sequence, which is not fully understood, was that although the values of local stress and strain at the extremities of half cycles 12 and 15 agreed closely with values previously obtained on half cycles of the same amplitude, the half cycles which followed, 13 and 16 respectively, both showed a local stress value at zero local strain slightly greater than that found on other earlier half cycles following loads of value P_3 (i.e. 2,3,6,7,8,11) and on subsequent half cycles (i.e. 14 and 21). This effect was observed on every individual specimen both notched and plain and indicates that the capacity of the material for strain hardening was slightly affected by the difference in the sequences $+P_3$, $-P_1$, $+P_1 - P_3$ and $-P_3$, $+P_1$, $-P_3$. A similar effect was found later in sequence 1 (see below) and in Sequence 2 (see section 7.2).

It may be anticipated from the foregoing discussion on half cycles 1-9 that the application of a cycle of intermediate amplitude between a large half cycle of load and subsequent low level cycles may reduce the value of residual stress resulting from the large half cycle. In order to explore this possibility, sequences (half cycles 15-24) were applied with such an intermediate cycle. The net stress amplitude of this cycle was chosen to be $\pm \frac{\sigma_y A}{K_t} = \pm P_2$. In the absence of the Bauschinger effect and cyclic strain hardening, this load amplitude is the highest at which fully elastic cycling would still occur - regardless of the state of residual stress before cycling commenced the material at the notch root would cycle between the tensile and compressive yield points, and the local mean stress would be zero. Therefore for a specimen at zero mean stress undergoing fatigue at this level, the residual stress would fall to zero during the first cycle. In this investigation it can be seen, from Figs.11 and 22, that this load cycle was effective in substantially reducing the values of residual stress due to the half cycles of value $+P_3$ and $-P_3$. In fact it would have been slightly better to use only one half cycle of amplitude P_2 since the second half cycle served only to increase (and incidentally to reverse) the value of residual stress.

Half cycles 25-27 and 28-30 (Figs.12 and 13) show sequences similar to those of half cycles 13-15 and 10-12 respectively, except that P_2 was substituted for P_1 in every case. It can be seen (Fig.13) that half cycles 28 and 31 show slightly steeper post yield stress vs. strain curves than other half cycles following a load of value P_3 (e.g. 26 and 29). This is an effect similar to that described above on half cycles 13 and 16, in that the effect occurred after a relatively small amount of reversed yielding had occurred on the preceding two half cycles.

Finally, half cycles 31-36 (Figs.14 and 15) show how residual stresses due to a load of amplitude P_4 can also be reduced to nearly zero by the application of a single half cycle of amplitude P_2 $\left(\text{net stress given by } \frac{\sigma_y}{K_t}\right)$. As previously, the residual stress was reduced closer to zero by the application of one half cycle of amplitude P_2 than by a full cycle.

7.2 Sequence 2 - positive mean stress

When a notched aluminium alloy specimen is subjected to fatigue loading the mean stress is of some importance in determining behaviour at the notch root. For instance, when local yielding occurs under fatigue loading at a positive mean stress, residual stresses thus generated are predominantly compressive unlike the zero mean stress case. Under finite mean stress conditions there is also a difference between the alternating stress at which yielding occurs on the first cycle only, and the alternating stress at which yielding will occur on subsequent cycles also.

Sequence 2 (Fig.5) represents the case where the mean stress was not on its own high enough to cause local yielding. The sequence was composed of a number of alternating loads with amplitudes designated in general $Q_{n/2}$ where n is the amplitude of the load in thousands of pounds. The amplitudes were such as to cover the two cases of yielding referred to at the end of the preceding paragraph, and later in the sequence large negative unidirectional loads were applied so as to simulate the effects of air-ground-air cycles. In Sequence 2 (Fig.5), half cycles 1-36 form a sequence of generally increasing loads interspersed with occasional low level cycles. The lowest load amplitude applied (half cycles 1 and 2 etc.) was in fact large enough to cause yielding on the first cycle, and so resulted in a negative residual stress at the end of half cycle 1 (Figs.16, 17 and 23). This residual stress was virtually unchanged at the end of half cycle 2 (cf half cycles 1 and 2 in Sequence 1). It can be deduced that any further stress cycling at that level would not produce any further substantial yielding on any one cycle. Therefore the material at the notch root would be subjected to the full elastic alternating stress ($K_t \sigma_a$), but the local mean stress $\sigma_{\ell m}$ would be less than the elastic mean stress so that:

$$\sigma_{\ell m} = K_t \sigma_m - \sigma_R$$

Half cycle 3 can be seen to have caused further local yielding as soon as the maximum stress of half cycle 1 was exceeded, thus increasing the negative residual stress and decreasing $\sigma_{\ell m}$. No significant further yielding occurred on half cycles 4-6. Yielding occurred however on both half cycles 7 and 8 ($\pm Q_4$) showing that in the absence of any cyclic strain hardening such cycles were above the level at which yielding would occur on every cycle (e.g. yielding also occurred on half cycle 11 which was the same amplitude as half cycle 7). At this alternating stress and above, therefore, the residual stress at the end of a positive half cycle differed from that at the end of a negative half cycle. It may be seen in Fig.23d how this variation between half and full cycle residual stresses increased with alternating net stress during half cycles 1-36. The corresponding general decrease in average residual stress with increasing alternating stress level - and hence decrease in local mean stress - can also be seen in Fig.23d.

On half cycles 24 ($-Q_2$) and 27 ($+Q_2$) some yielding occurred, alleviating to some extent the residual stress state produced by the preceding half cycles, 23 ($+Q_6$) and 26 ($-Q_6$) respectively - a situation similar to that found in half cycles 2 and 3 of Sequence 1.

Half cycles 34-44 (see Figs.17 and 24) demonstrate the slight but progressive alleviation, with increasing alternating stress level, of the residual stresses due to a high tensile load, half cycle 33 ($+Q_6$). The effect can be seen to be similar to that found on half cycle 1-33 of Sequence 2 in that, under the lower level half cycles 34-37 ($\pm Q_2$) and $\pm Q_3$) yielding (in this case compressive) only occurred on the first (compressive) quarter cycles of any amplitude and so any subsequent cycling at that level would have been expected to occur under elastic conditions. The amount of yielding on half cycles 34-37 at any particular level however was not as great as was found on the corresponding cycles earlier at the beginning of Sequence 2. This would of course depend on the magnitude of the initial half cycle (33). However the level at which fully reversed yielding occurred (on half cycles 38-39) was the same as previously ($\pm Q_4$). Half cycles 45-55 (Figs.18 and 24) show a similar sequence to the foregoing except that the rising sequence of loads was preceded by a negative load, half cycle 44 ($-Q_6$). Again, the level at which fully reversed yielding occurred was the same as previously ($\pm Q_4$) on half cycles 49-50).

With the two rising sequences (34-44 and 45-55) it can be seen that as the alternating loads increased, the residual stress histories gradually became the same for both sequences over a half cycle of any particular amplitude - note the corresponding half cycle stresses of half cycles of the same amplitude from the two sequences (Figs.17 and 19).

Half cycles 56-70 illustrate the effects of large negative loads (58, 62, 64, 68, i.e. $-Q_8$, $-Q_9$, $-Q_{11}$ and $-Q_{11}$) on the residual stress state. An interesting point here is of course the large amount of reverse yielding occurring under these loads, none of which would be expected to produce yielding without the initial tensile yielding. Such loads therefore can reduce the value of the compressive residual stresses and hence create an increased rate of fatigue damage under subsequent low level cycles.

In section 7.1 it was shown that minor differences in load sequence may alter the shape of the post-yield stress vs. strain curve of the material at the root of the stress concentration, in subsequent cycles. In Sequence 2 similar effects can be seen where there are large differences between the compressive post-yield curves of half cycles 16 and 22, and 30 and 44 (see Fig.17). It is not yet clear which aspects of the loading sequence were responsible for this effect. However, it does seem to be associated with small amounts of prior reversed yielding, and indicates the possibility that the capacity of the material for sustaining residual stresses may be affected by prior reversed yielding under relatively low level cycles.

7.3 General remarks

The work described in this Report has shown in detail how residual stresses at the root of a notched aluminium alloy component can vary depending on the loading action applied. The effect of such stresses, if tensile, following the application of a large compressive load, is to increase the rate of fatigue damage at least in the early stages of fatigue life by acting as a superimposed mean stress at the notch root and so changing the local mean stress. Conversely, compressive residual stresses following tensile yielding produce a decrease in fatigue damage rate. The variation in residual stress is complicated by the Bauschinger effect - the decrease in absolute value of the compressive yield point by initial tensile yielding (and vice versa).

A result of this can be to cause compressive local yielding under air-ground-air cycles in aircraft even when the local stress at the notch root is only just compressive (see Fig.17, half cycle 16). Additionally, due to the presence of compressive residual stresses, compressive yielding can occur at the notch root whilst the net stress is still tensile, (e.g. Figs.16 and 17, half cycle 16). Compressive yielding accentuates the damaging effect of cycles immediately following air-ground-air cycles and so can cause large errors when using the linear cumulative damage hypothesis (Miner's Rule).

Even in the absence of air-ground-air cycles, when predicting the fatigue life of a component under one loading action from data obtained under another loading action (e.g. when predicting life under variable amplitude loading from data obtained under constant amplitude loading) it is often important to account for differences in residual stress state caused by the two different loading actions. A particular example where failing to account for these effects can lead to errors, is the fact that Miner's Rule usually underestimates the fatigue life of notched aluminium alloy specimens when loaded at a positive mean stress[1]. Methods are in fact being developed to predict life, taking into account these effects[1,5]. However, it is not possible to begin to predict the effects of residual stresses unless their magnitude is known. The technique described in this Report provides a useful method of measuring at least surface stresses at the point of fatigue initiation (assuming an initially stress-free component). Finite element methods of stress analysis provide a possible means of determining complete stress distributions under conditions of yielding and it should eventually be possible, with a knowledge of crack propagation behaviour in the presence of residual stresses (generated both by the geometric stress concentrations and by the crack itself) to predict the rate of growth of fatigue damage in structural components throughout the entire life. However, for the present, knowledge of surface stresses at stress concentrations can at least give a qualitative estimate of fatigue behaviour over a substantial proportion of the fatigue life.

When testing components under a simulated service loading action by using a block programme, the stress history of the service component at the point of fatigue initiation should be assessed where possible and the block programme designed to give a similar variation. Of particular importance is the manner in which any constant amplitude block finishes before changing to a lower level, i.e. positive half cycle or negative half cycle, with a sharp change to the next level as with an electrohydraulic fatigue machine, or a relatively slow decay down to the next level as with the resonant type of fatigue machine. It is implied by the results of this programme that the largest residual stresses will usually be left after a sharp reduction in amplitude at the end of a block in a block programme and it will be less after a change in level which occurs over several cycles. The position of an air-ground-air cycle in a block programme should clearly be chosen with care. It should not be forgotten however that the best way to ensure a representative variation of residual stress is to apply a representative sequence of loads. This should be done wherever possible.

8 CONCLUSIONS

8.1 The local stress histories at the root of notched L65 aluminium alloy specimens under two variable amplitude load sequences have been determined. Two load sequences were applied to the notched specimen. Sequence 1 was at zero net mean load, and Sequence 2 at a positive net mean load.

In Sequence 1 it was shown how residual stresses, which may affect subsequent fatigue behaviour, can be formed by large positive or negative unidirectional loads or by the last half cycle of a high level loading sequence. The direction of the residual stress was in the opposite sense to the direction of the high level half cycle and could often be considerably alleviated by the first cycle of any subsequent cyclic stressing at a lower amplitude. The residual stress could be reduced close to zero by the application of a single half cycle of net stress amplitude $\frac{\sigma_y}{K_t}$ in the opposite direction to the high level half cycle.

8.2 In Sequence 2, the sequence at a positive mean stress, it was shown that residual stresses were predominantly compressive. It was also shown that below a particular alternating stress level, if local yielding occurred it was only on the first quarter cycle. Above this level yielding occurred on every half cycle and would be expected to continue under stressing at this level. Compressive yielding was noted under negative net half cycles just after the local stress reached compression and before the net stress reached compression, demonstrating how air-ground-air cycles may generate residual stresses which adversely affect fatigue life.

8.3 When testing components under a simulated service loading action by using a block programme, the residual stress history of the service component at the point of fatigue initiation should be assessed where possible and the block programme designed to give a representative variation. Representative loading sequences should be applied whenever practicable.

SYMBOLS

A	=	net cross sectional area of notched specimen
K_t	=	stress concentration factor
	=	$\frac{d\sigma_\ell}{d\sigma_n}$ under elastic conditions
σ_a	=	net alternating peak stress
σ_ℓ	=	local axial stress at stress concentrations
$\sigma_{\ell m}$	=	local mean stress
σ_m	=	net mean stress
σ_n	=	net stress
σ_R	=	residual stress
σ_y	=	yield stress
ε_ℓ	=	local strain

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5	C. R. Smith	Linear strain theory and the Smith Method for predicting the fatigue life of structures for spectrum type loading. ARL 64-55 (April 1964)

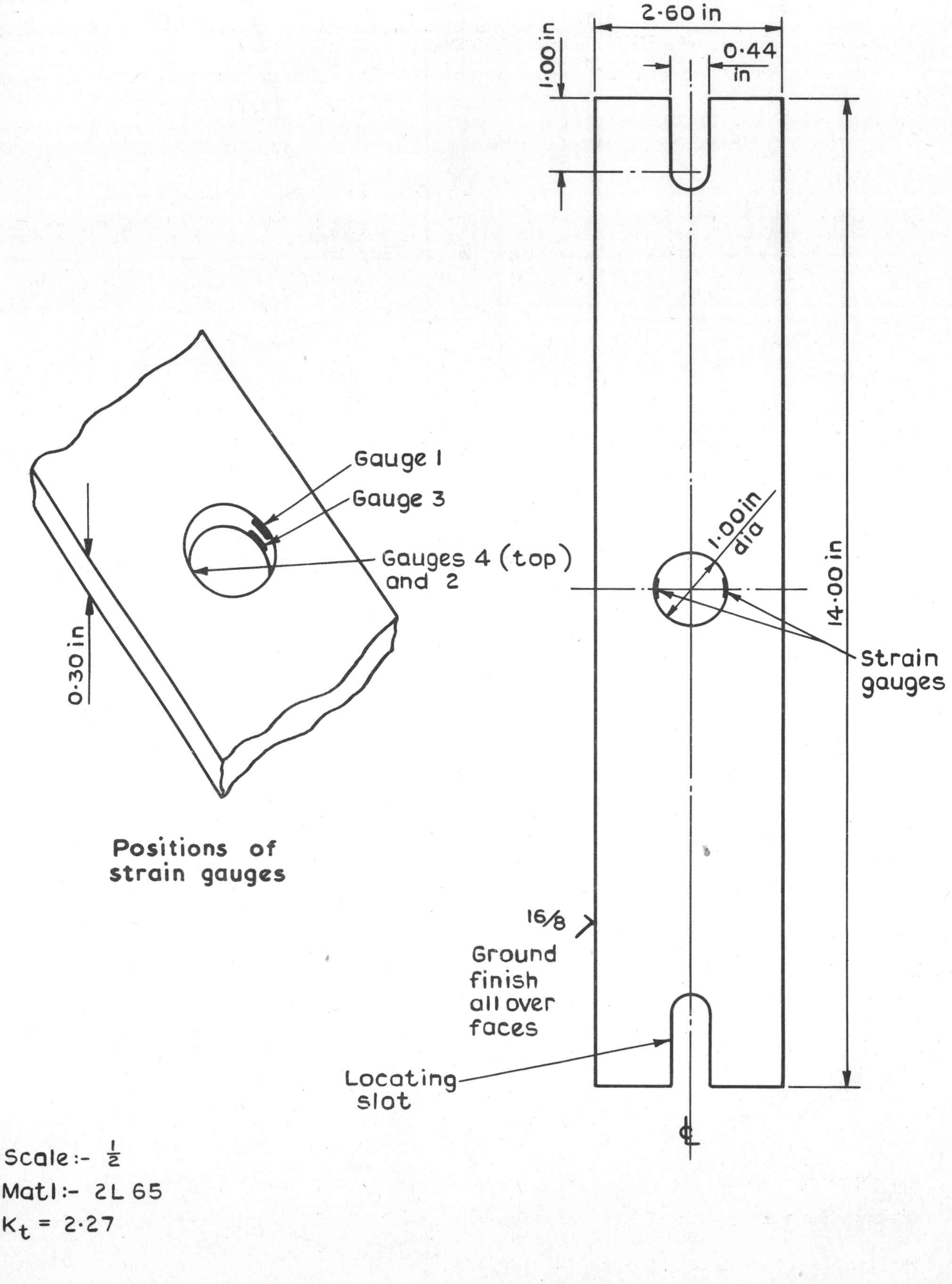
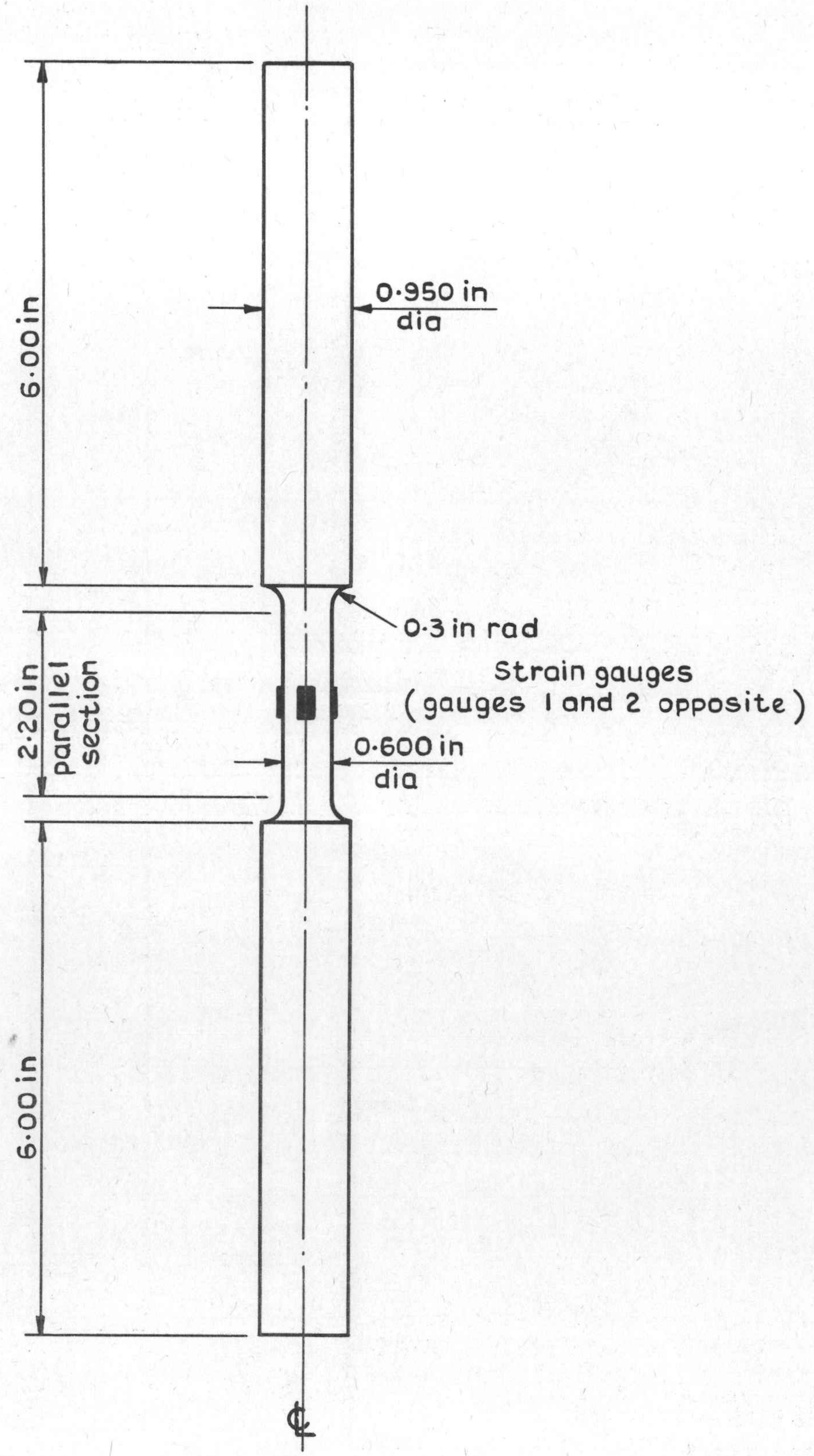


Fig. 1 Notched specimen



Scale :- $\frac{1}{2}$
Matl :- 2L 65

Fig.2 Plain specimen

NEG.NO.C6516 T.R.70004

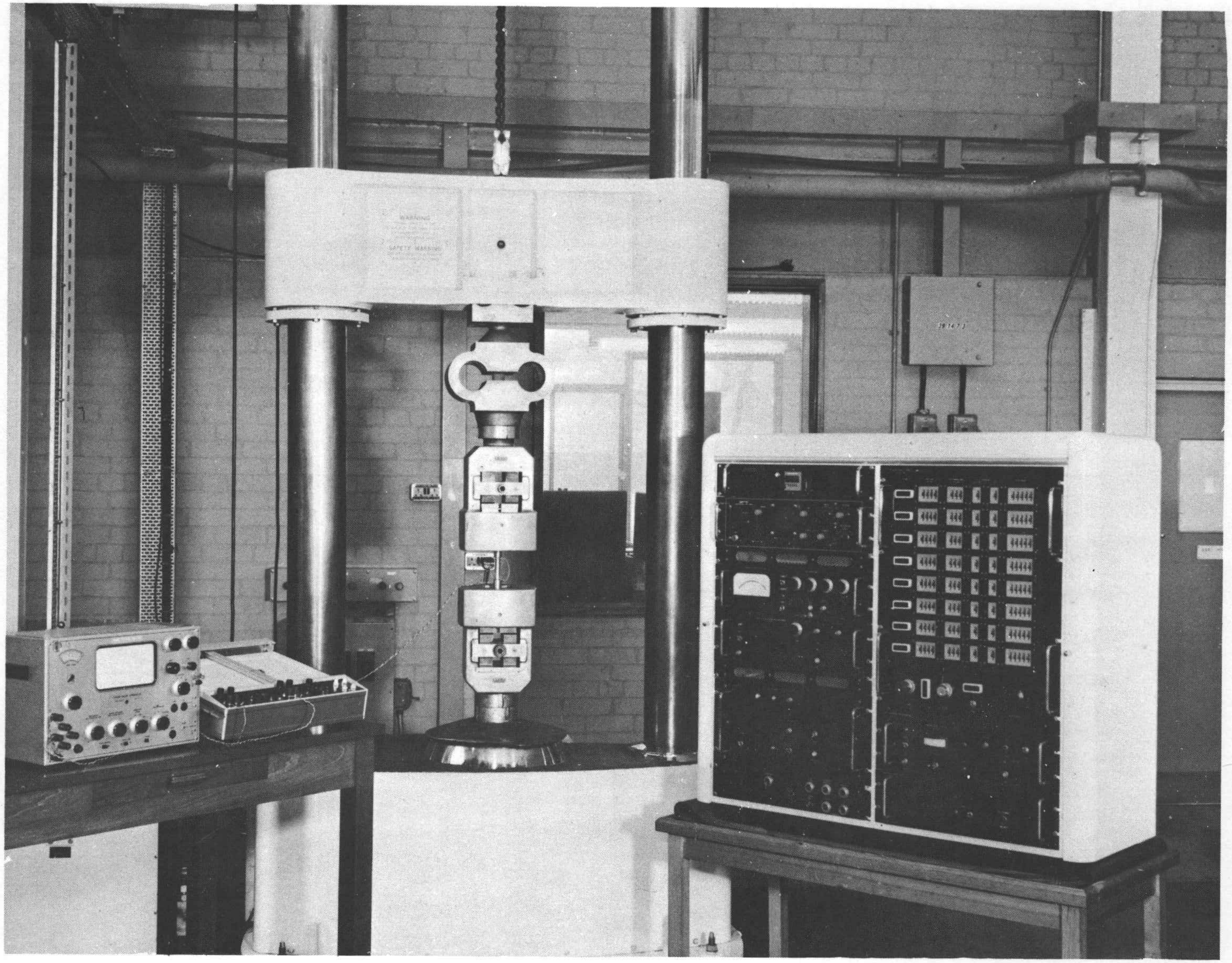


Fig.3. Fatigue machine

011905219

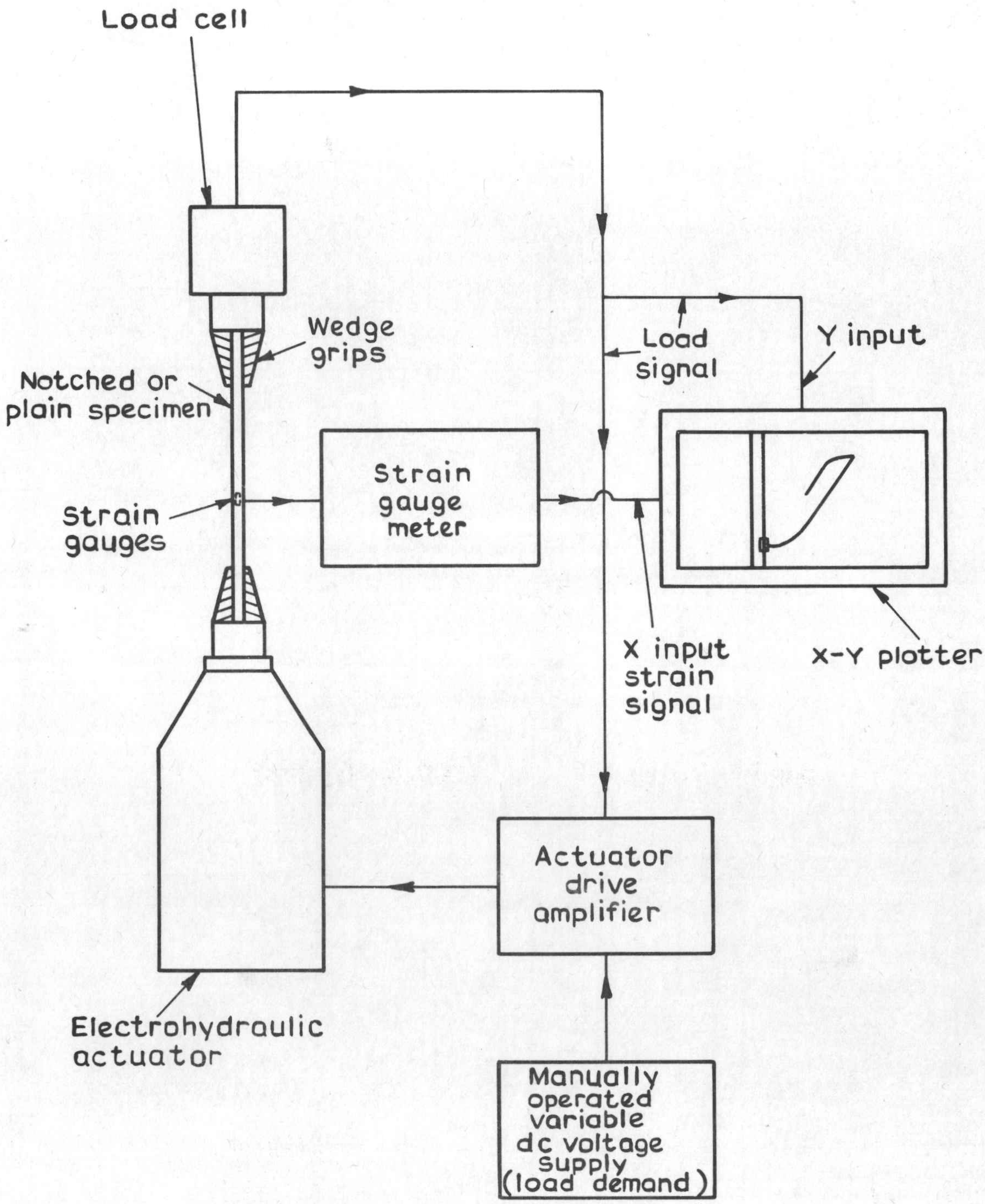
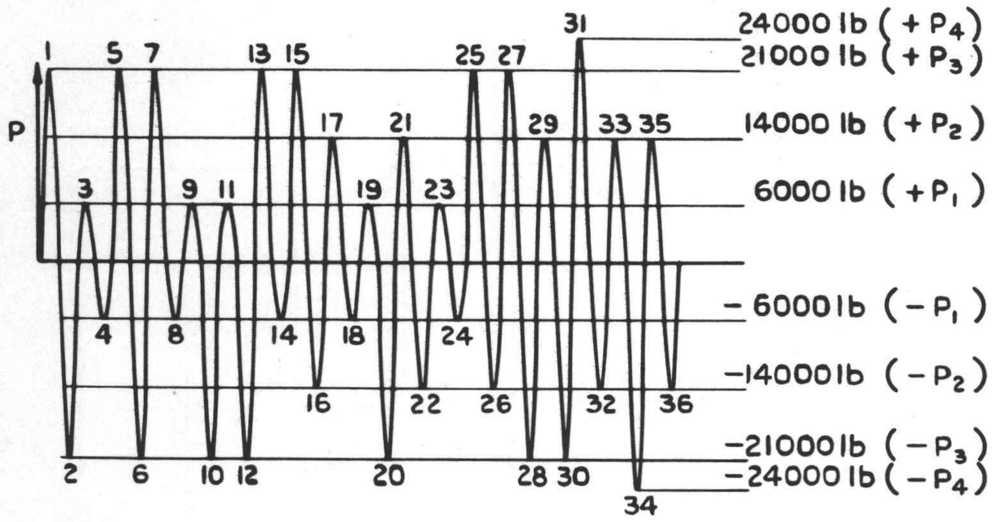
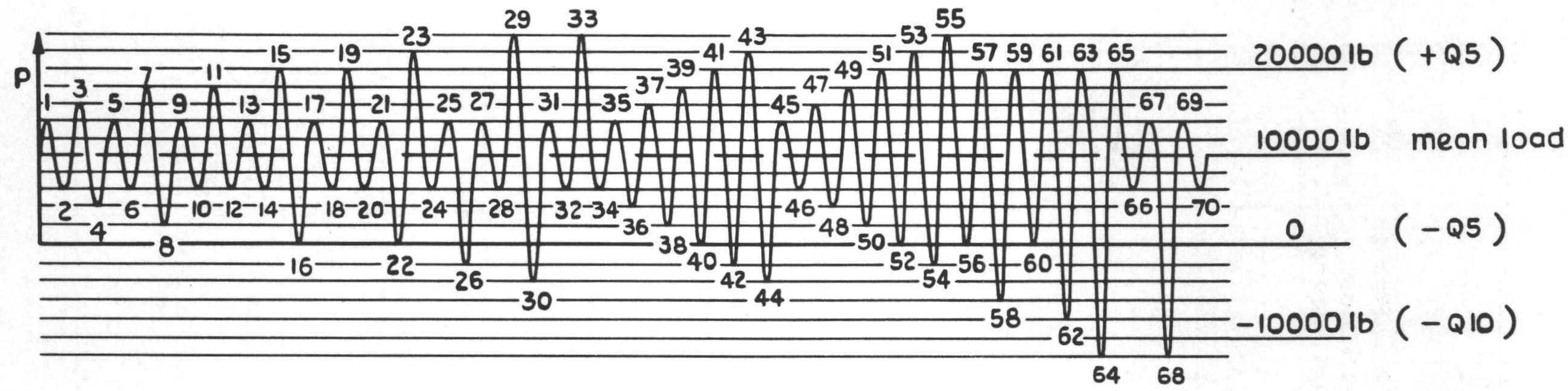


Fig.4 Schematic diagram of test arrangement



a Sequence 1 (zero mean stress)



b Sequence 2 (tensile mean stress)

Fig.5a&b Loads applied to notched specimen

011 905220

Fig.5a&b

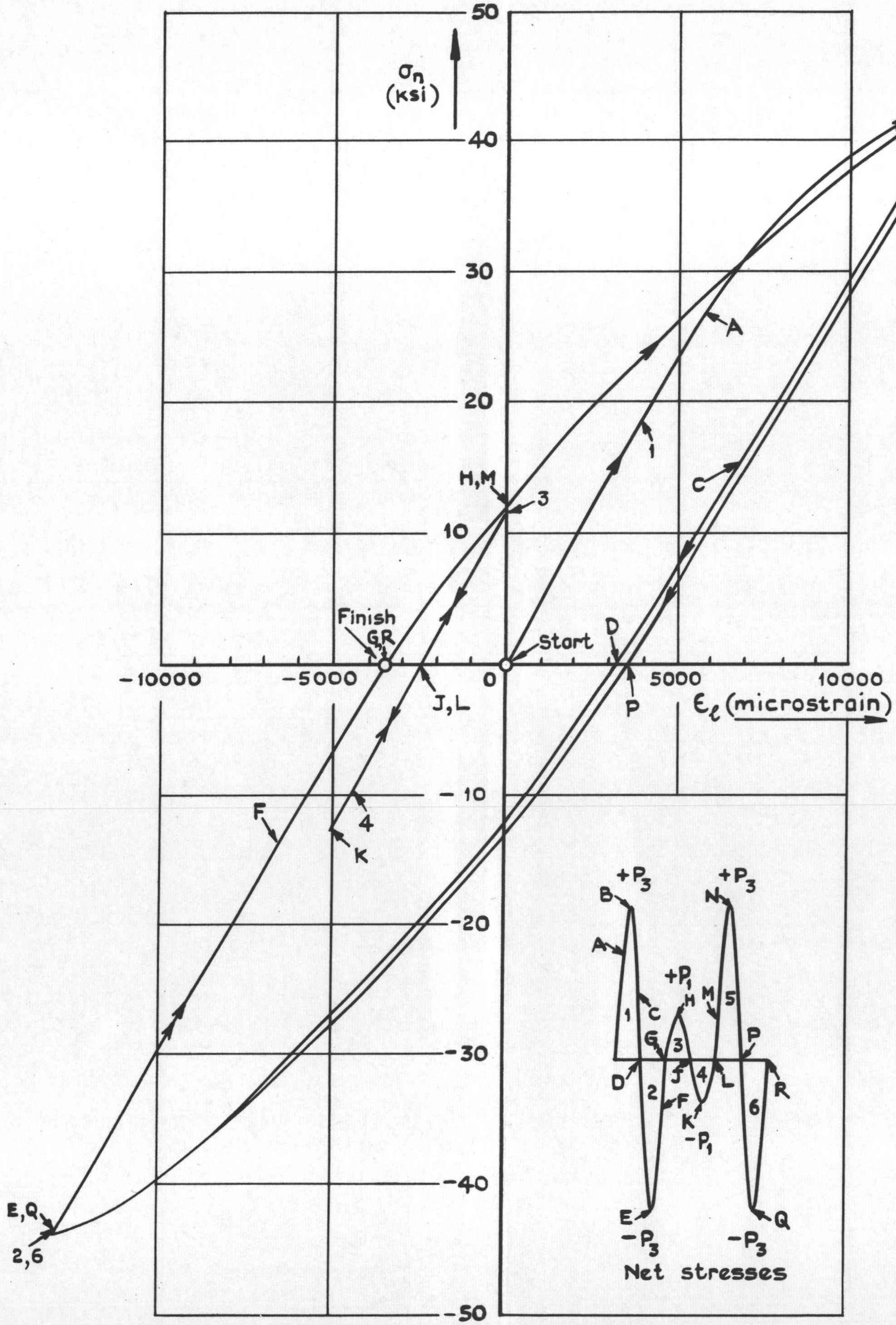


Fig. 6 Notched specimen 1st sequence $\frac{1}{2}$ cycles 1–6

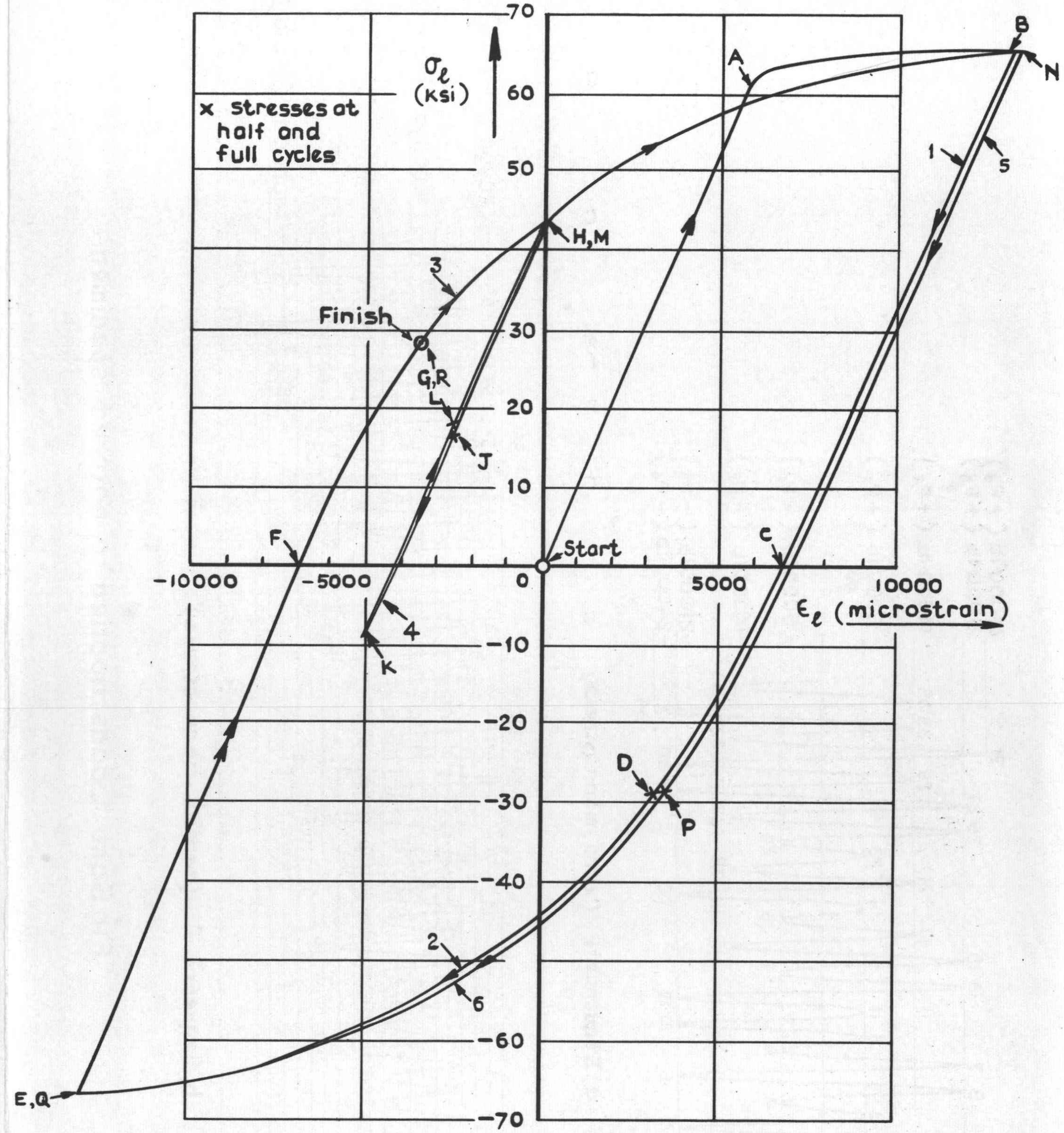


Fig. 7 Plain specimen 1st sequence $\frac{1}{2}$ cycles 1–6

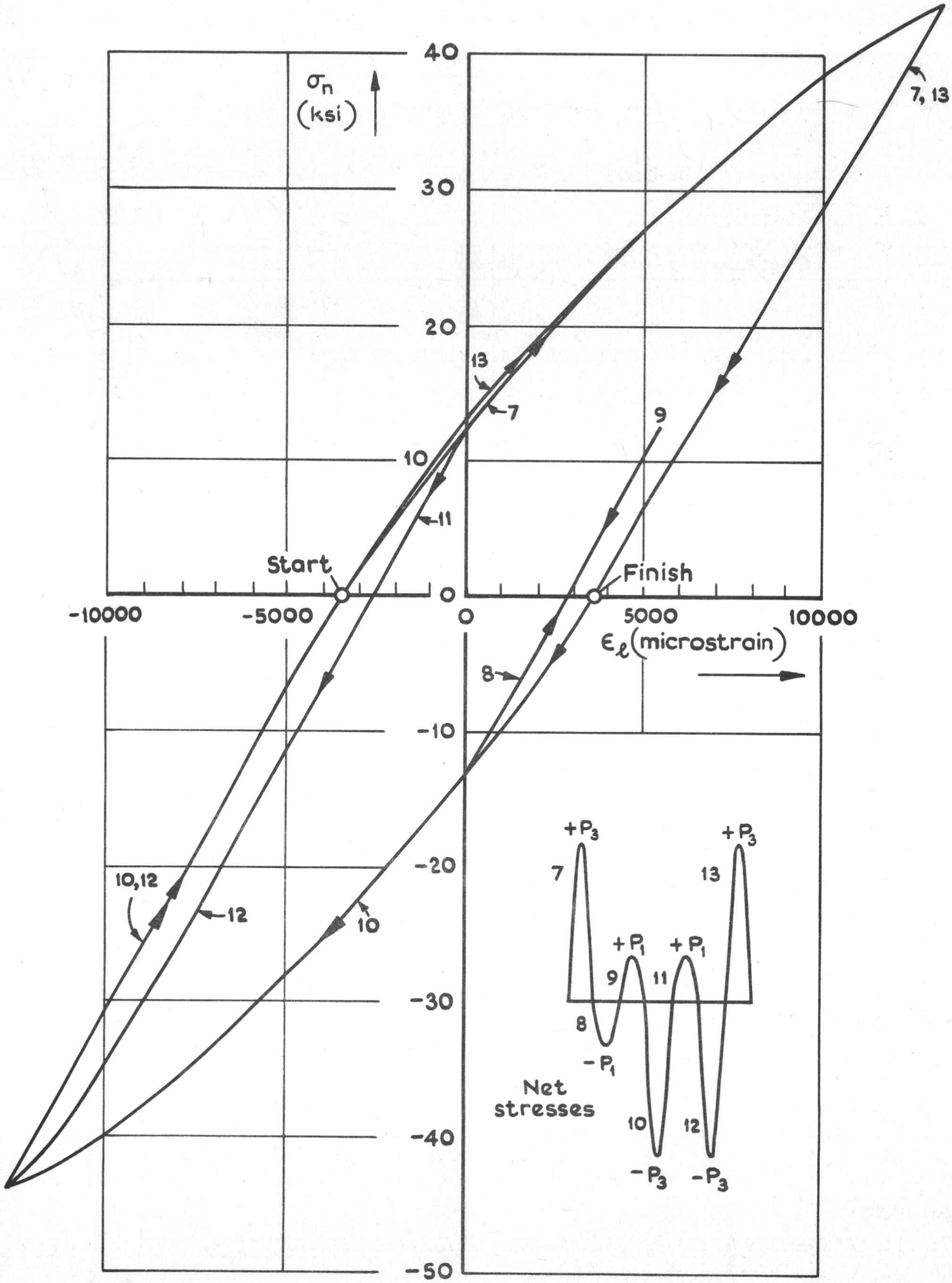


Fig.8 Notched specimen 1st sequence
½ cycles 7 - 13

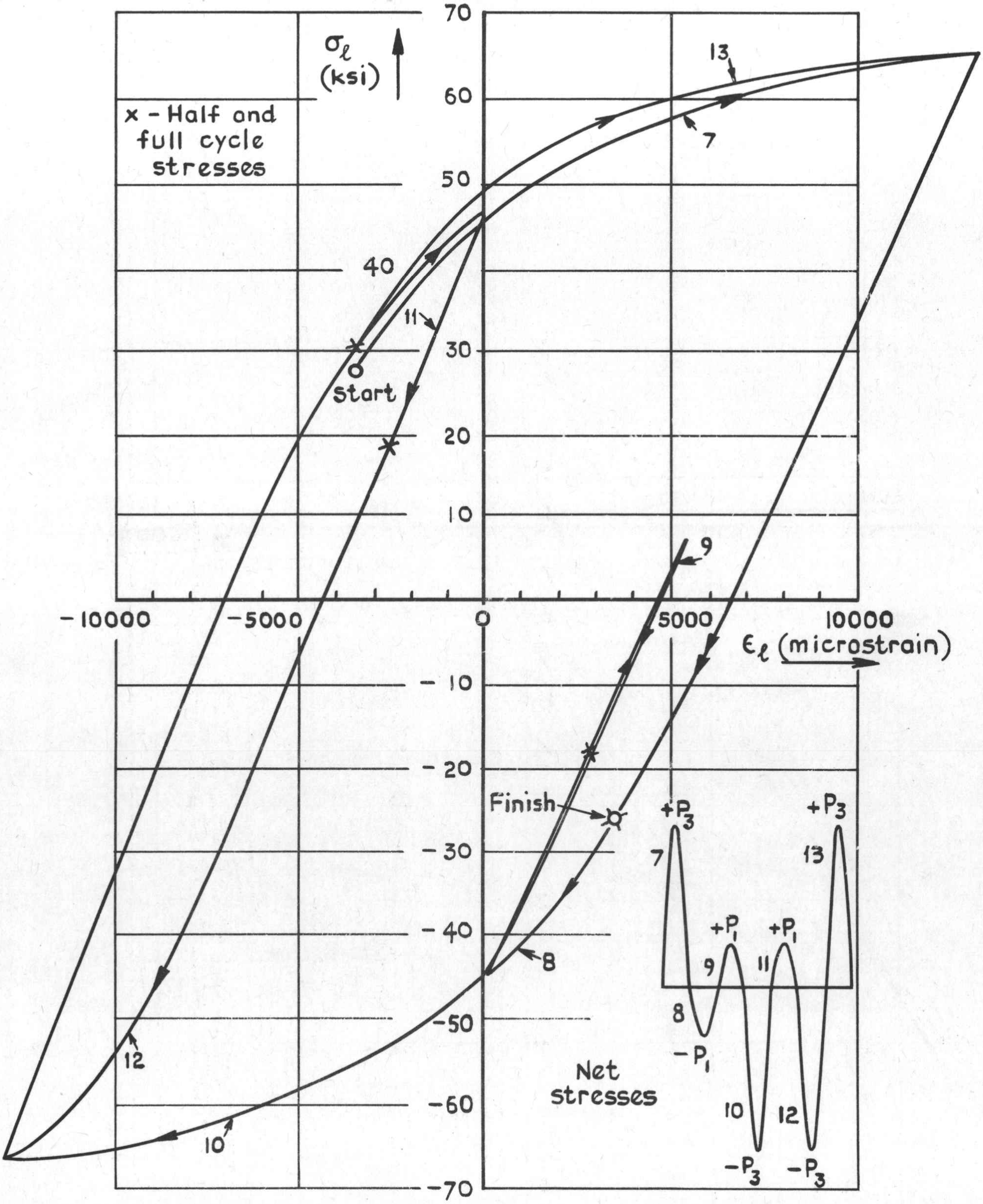


Fig. 9 Plain specimen 1st sequence $\frac{1}{2}$ cycles 7–13

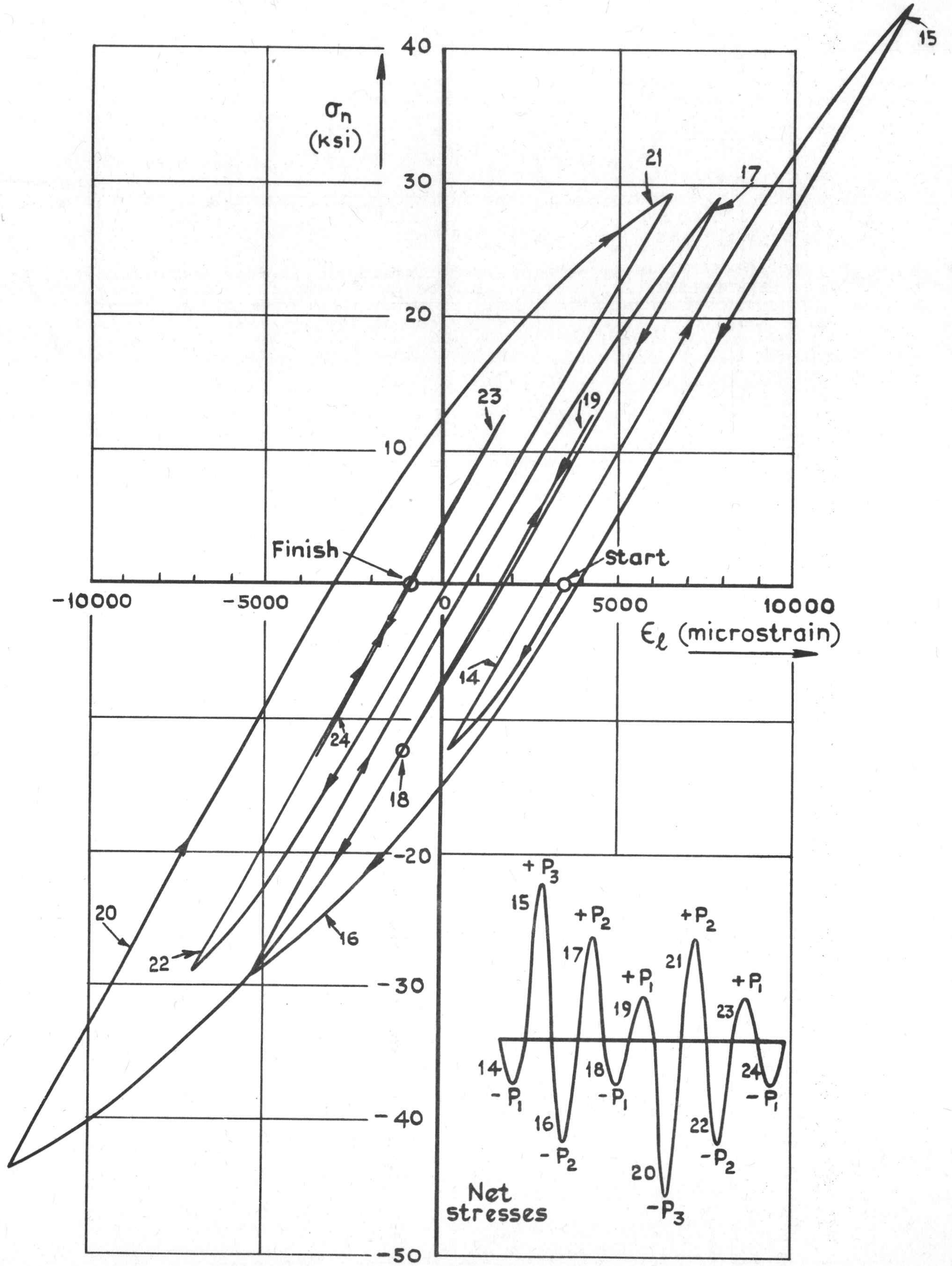


Fig.10 Notched specimen 1st sequence
$\frac{1}{2}$ cycles 14–24

Fig. 11

011 905226

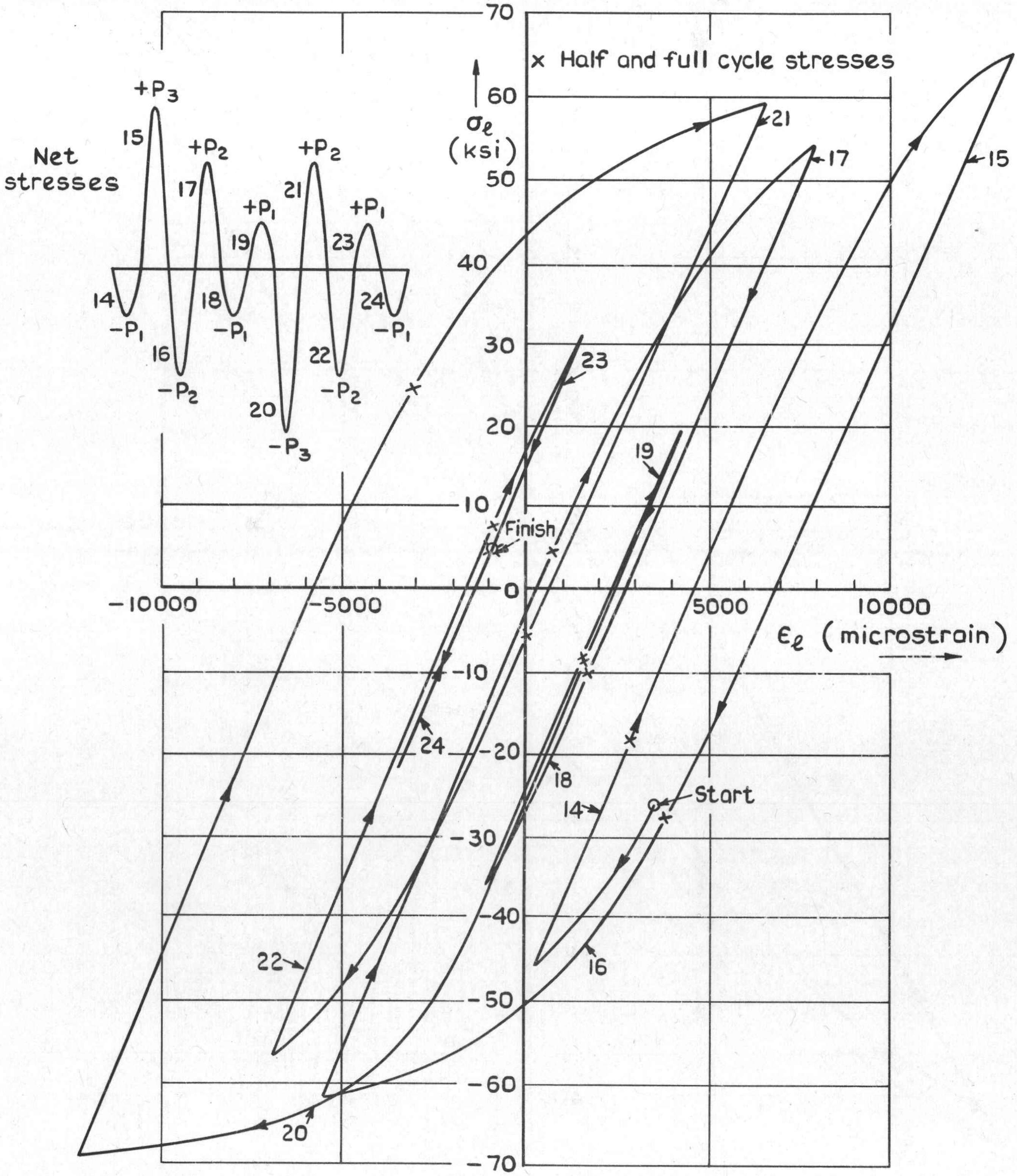


Fig.11 Plain specimen $\frac{1}{2}$ cycles 14–24

T.R. 70004

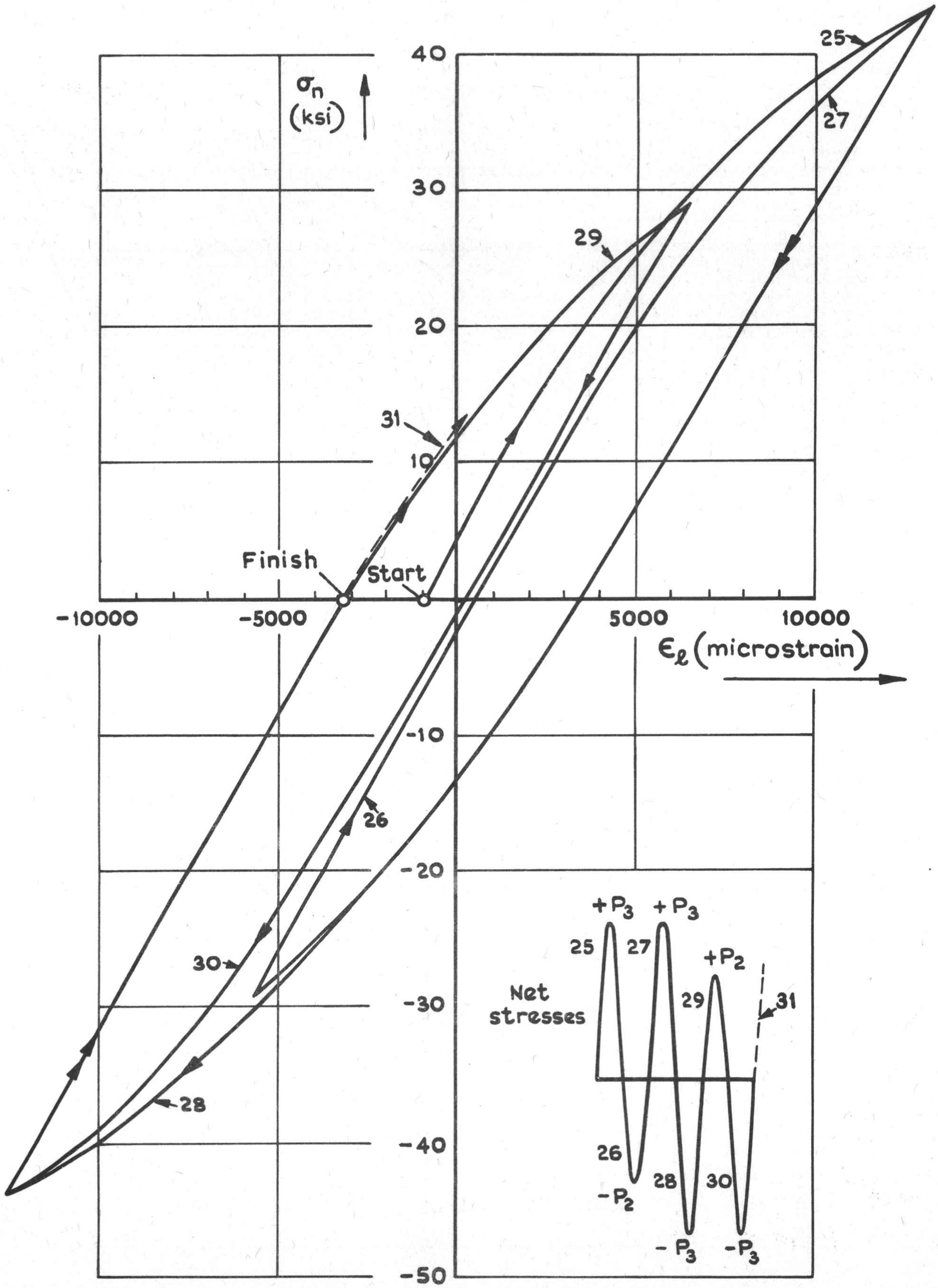


Fig. 12 Notched specimen 1st sequence

½ cycles 25-30

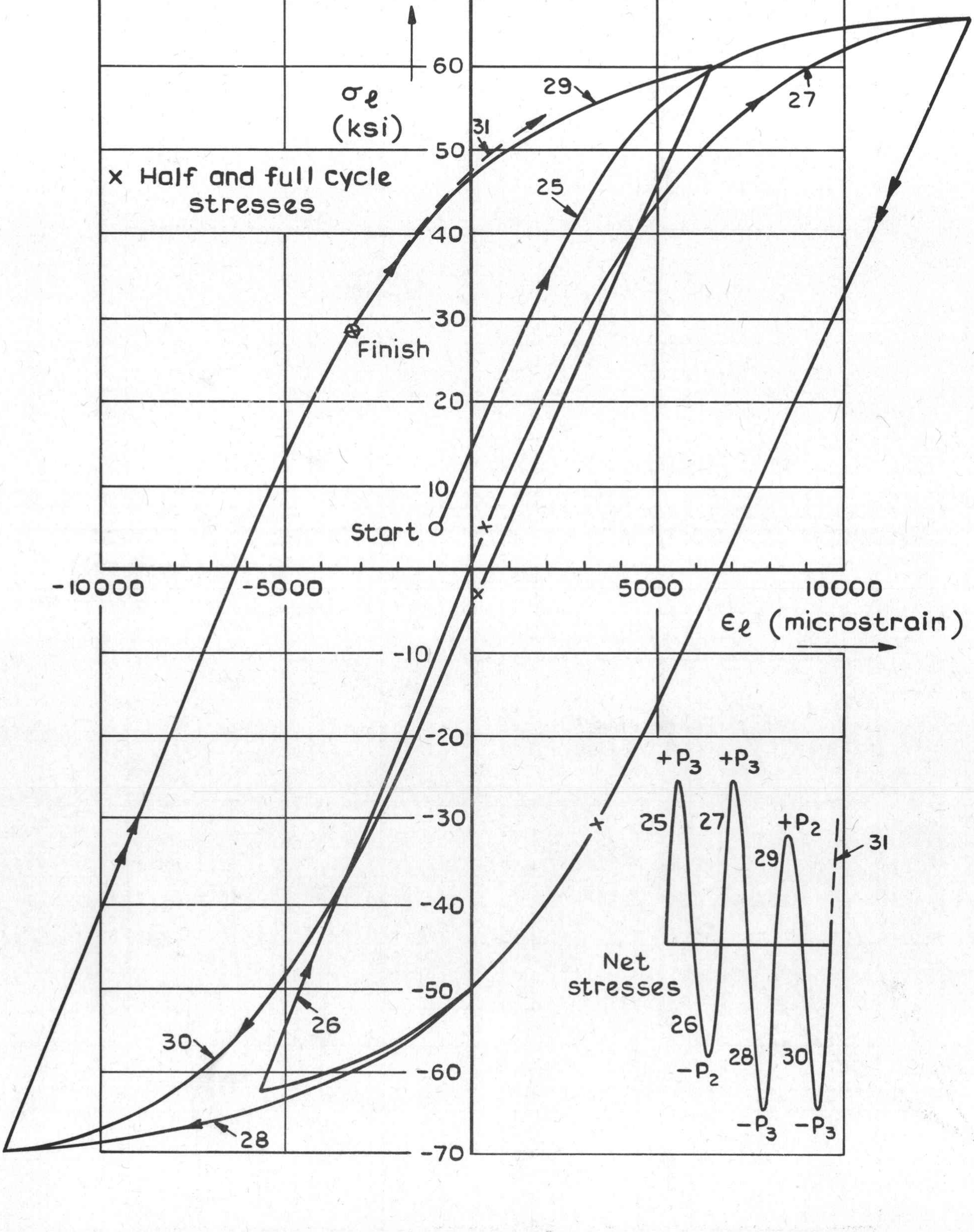


Fig.13 Plain specimen $\frac{1}{2}$ cycles 25–30

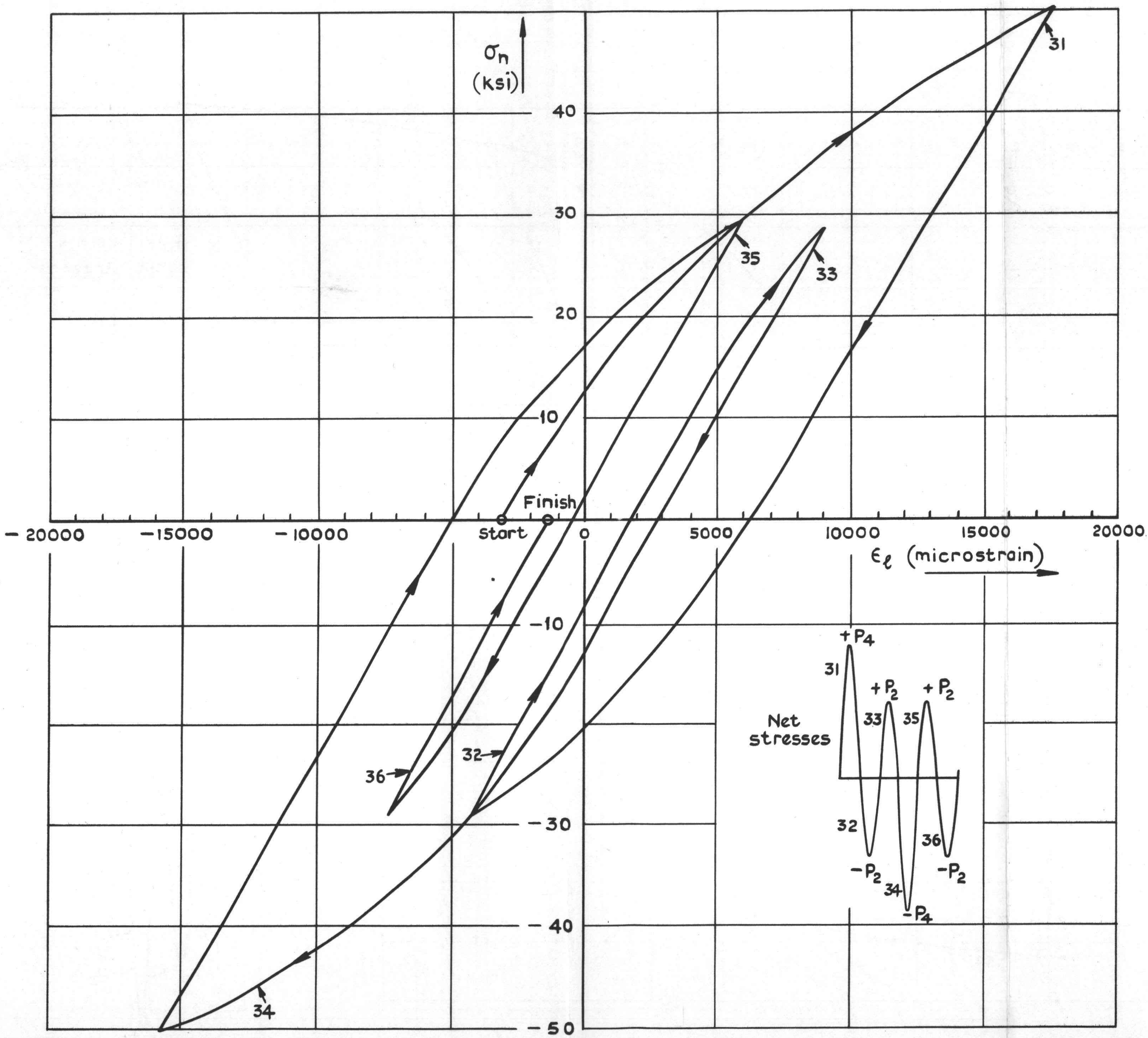


Fig.14 Notched specimen $\frac{1}{2}$ cycles 31–36

011 905230

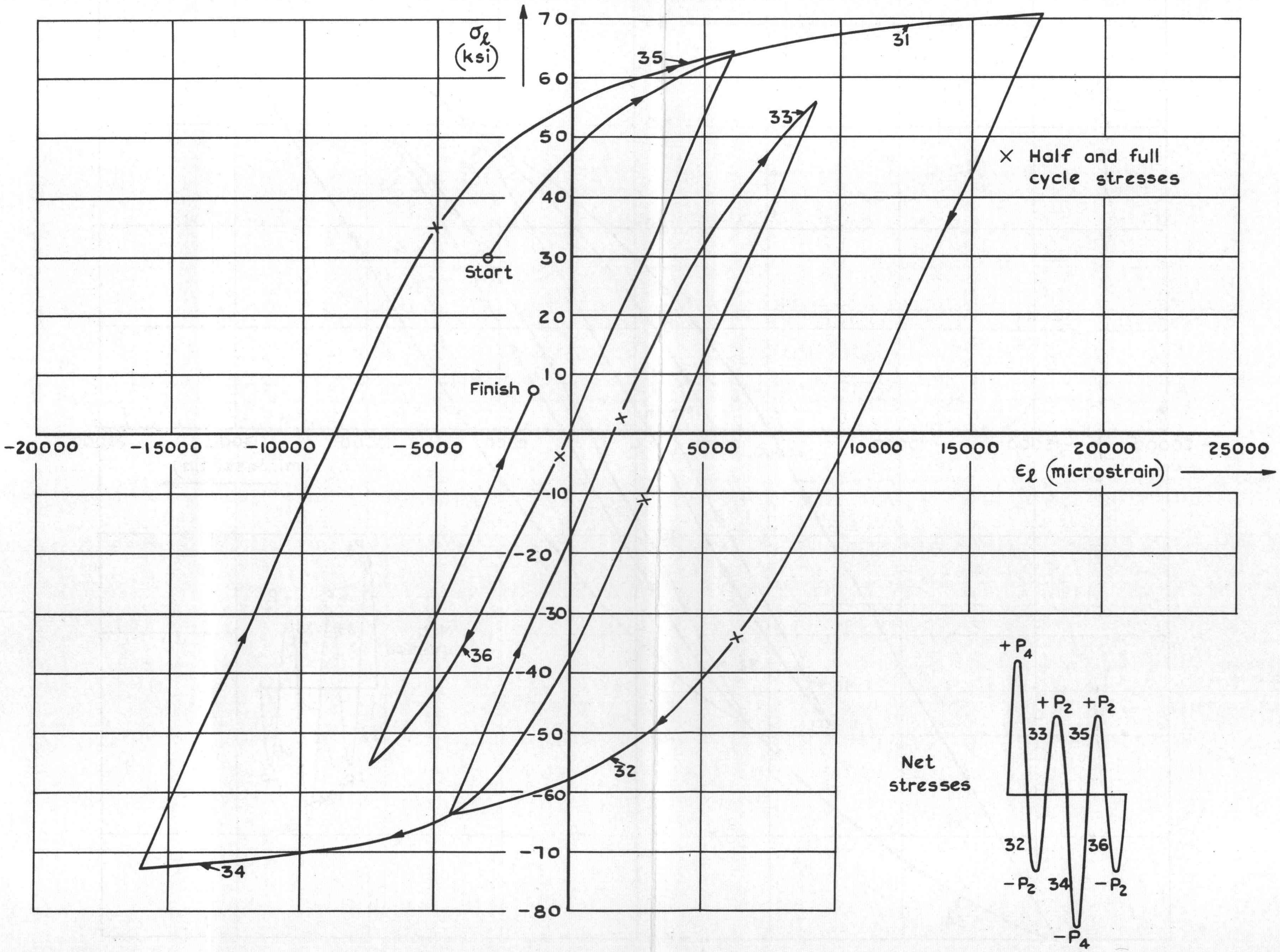


Fig.15 Plain specimen 1st sequence ½ cycles 31–36

T.R 70004

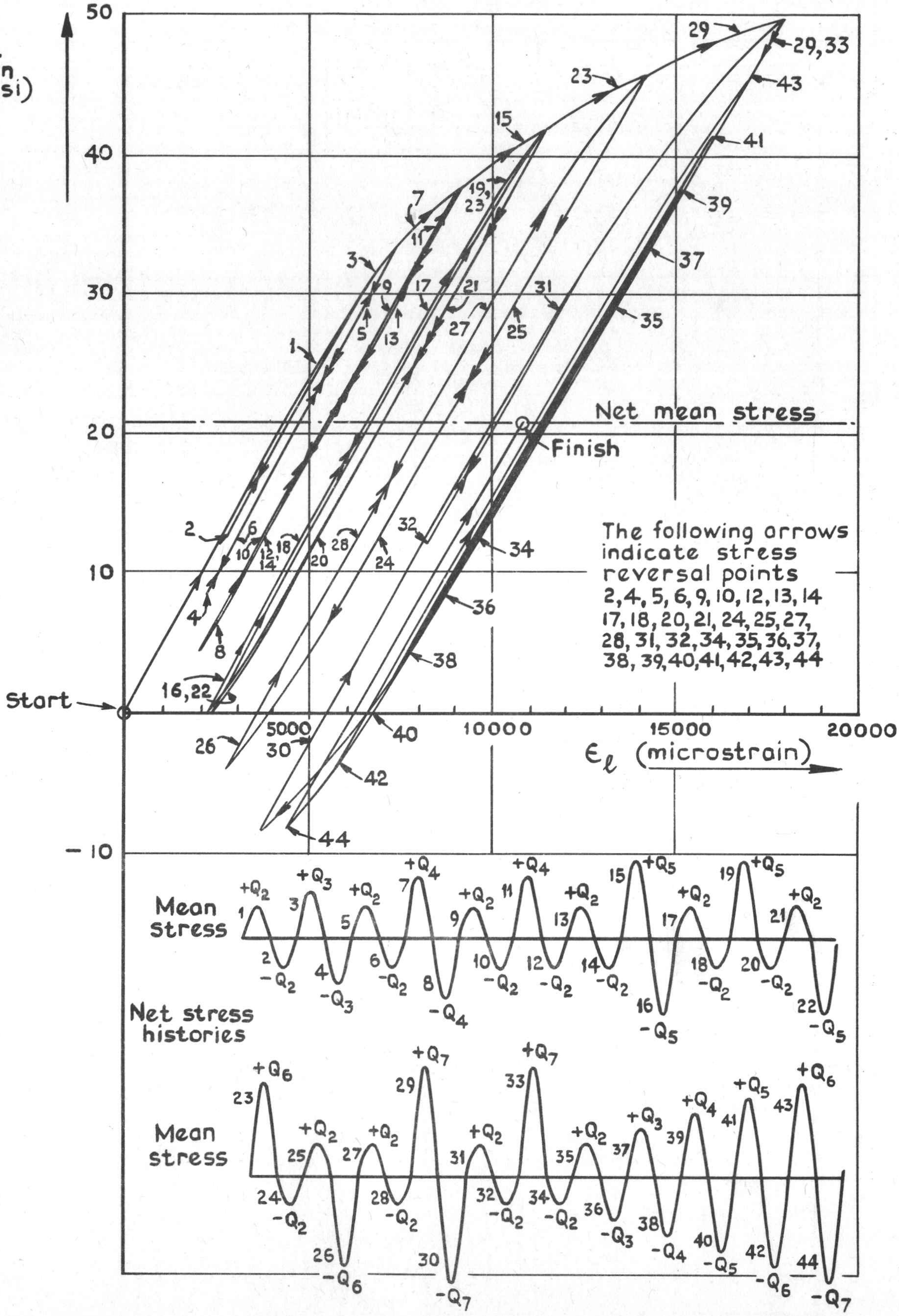


Fig.16 Notched specimen 2nd sequence $\frac{1}{2}$ cycles 1-44

Fig.17

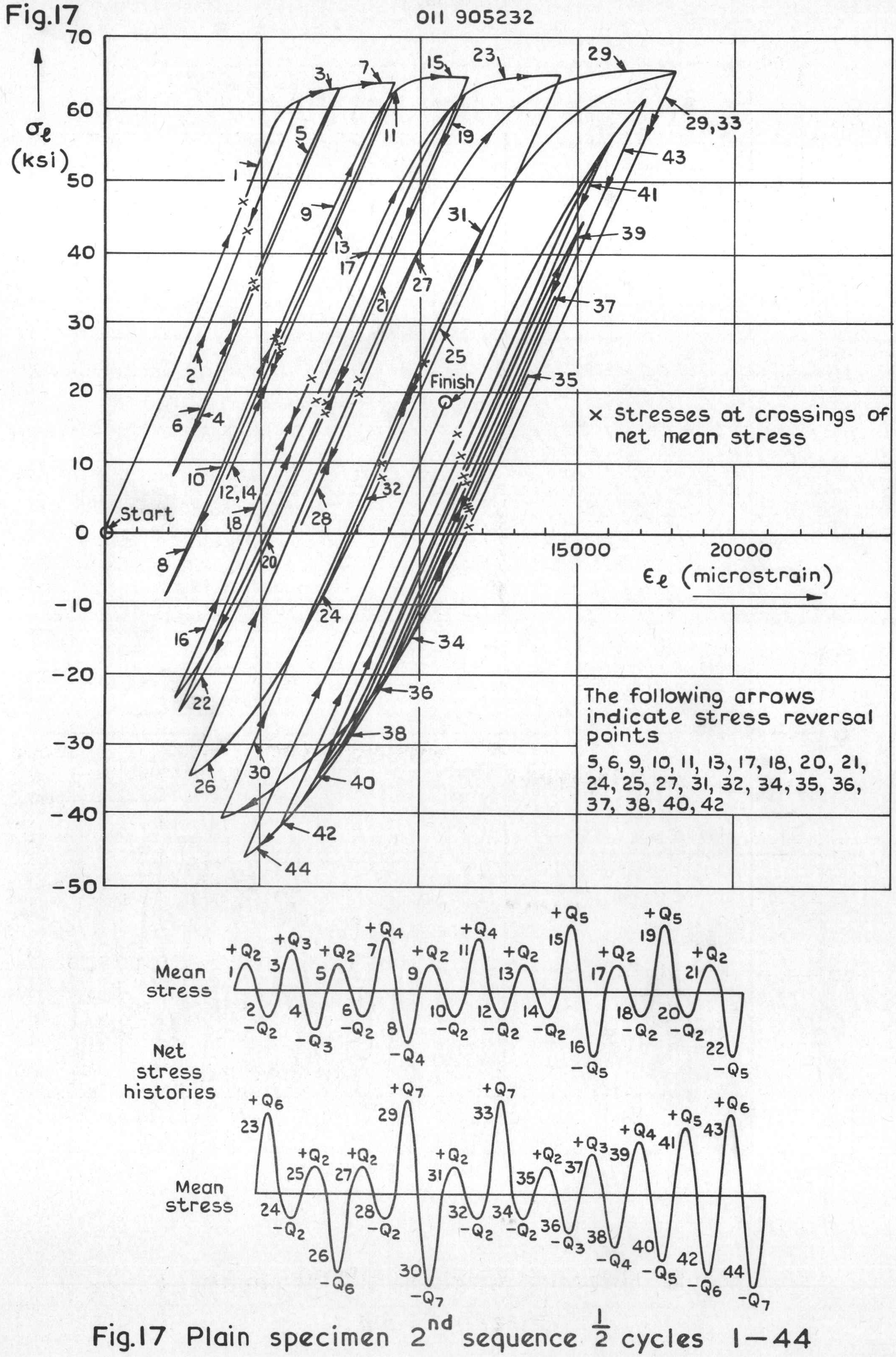


Fig.17 Plain specimen 2nd sequence ½ cycles 1–44

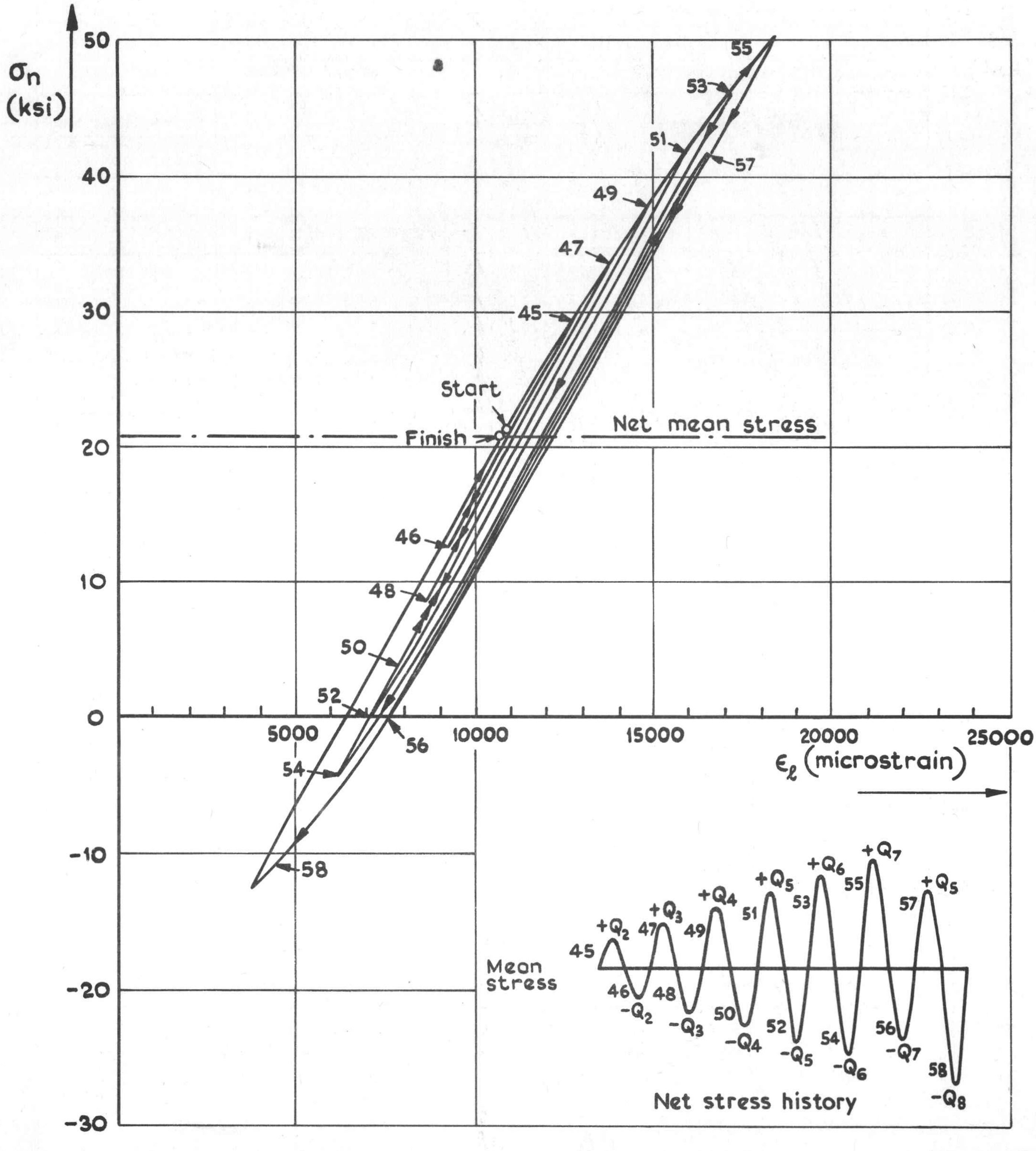


Fig.18 Notched specimen 2nd sequence

$\frac{1}{2}$ cycles 45 - 58

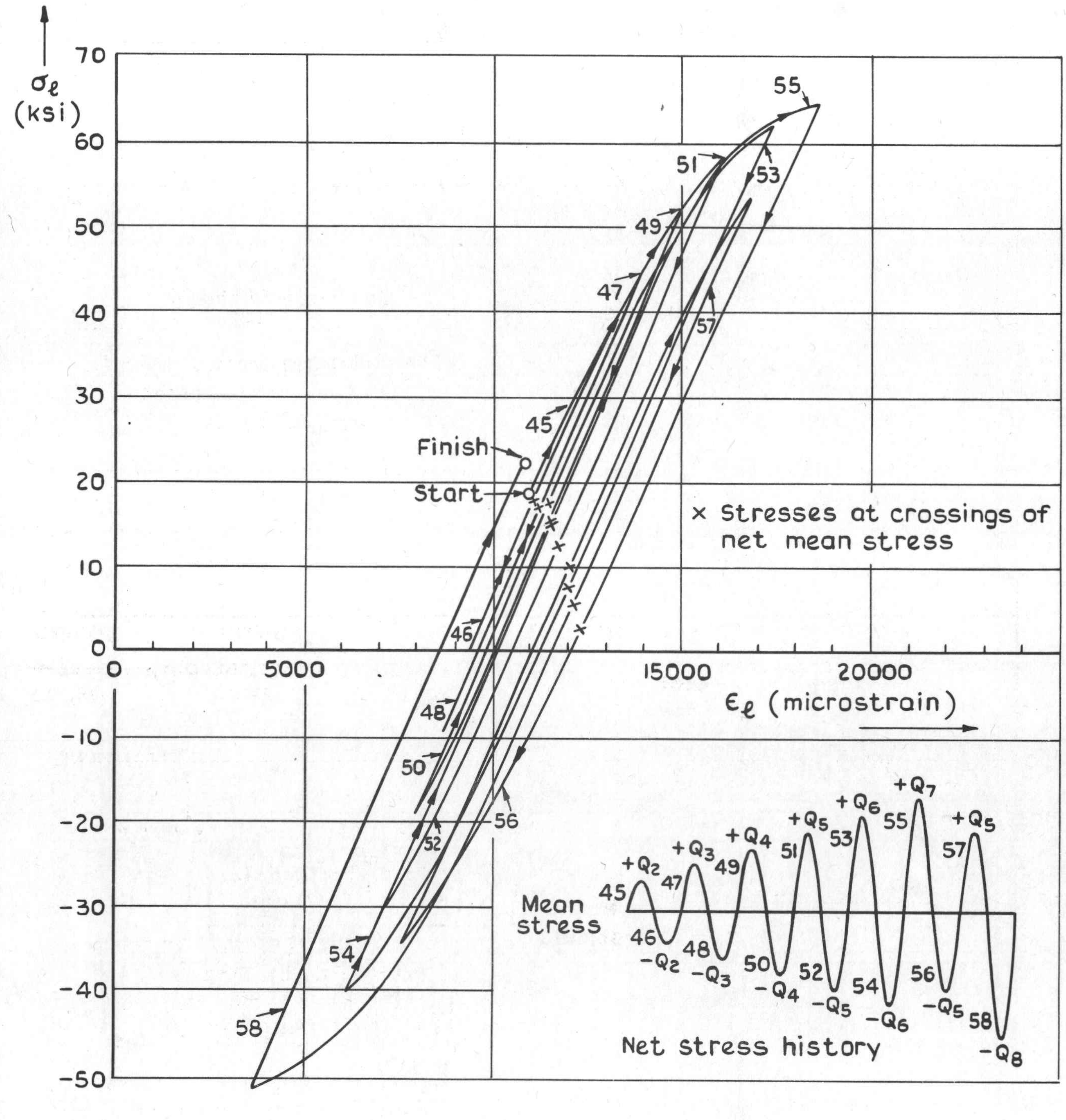


Fig. 19 Plain specimen 2nd sequence ½ cycles 45–58

T.R. 70004

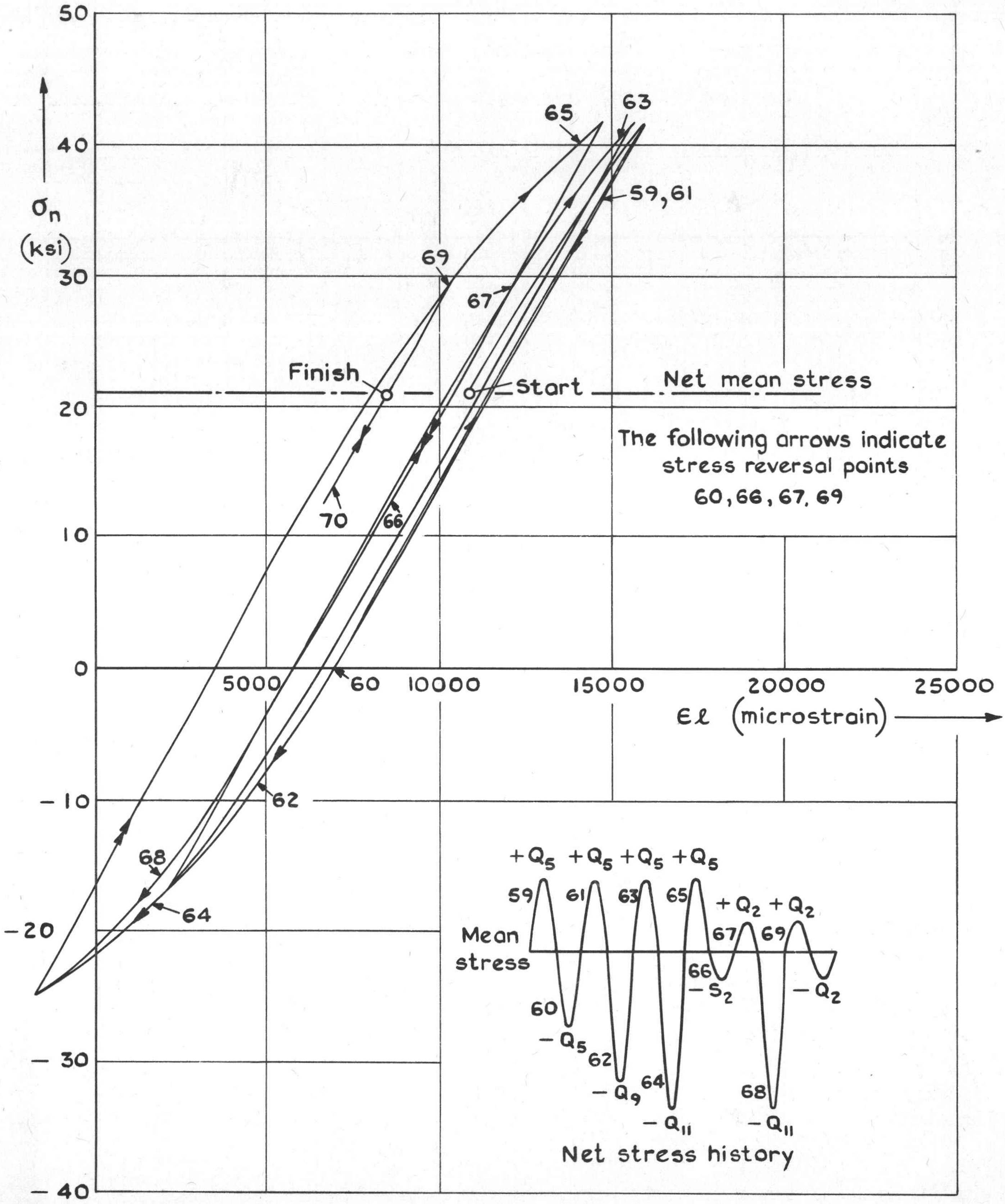


Fig. 20 Notched specimen 2nd sequence $\frac{1}{2}$ cycles 59–70

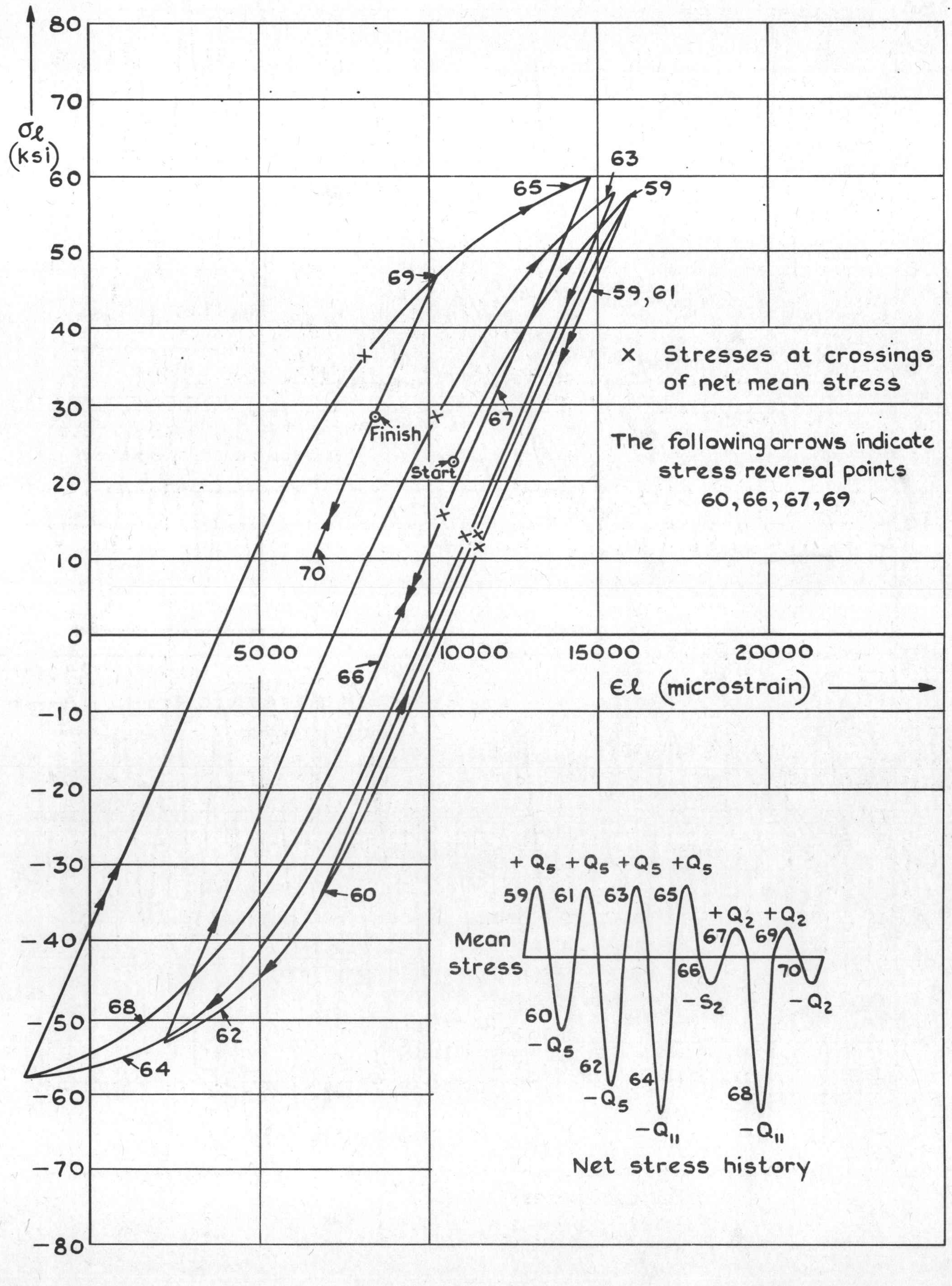


Fig. 21 Plain specimen 2nd sequence $\frac{1}{2}$ cycles 59–70

T.R 70004

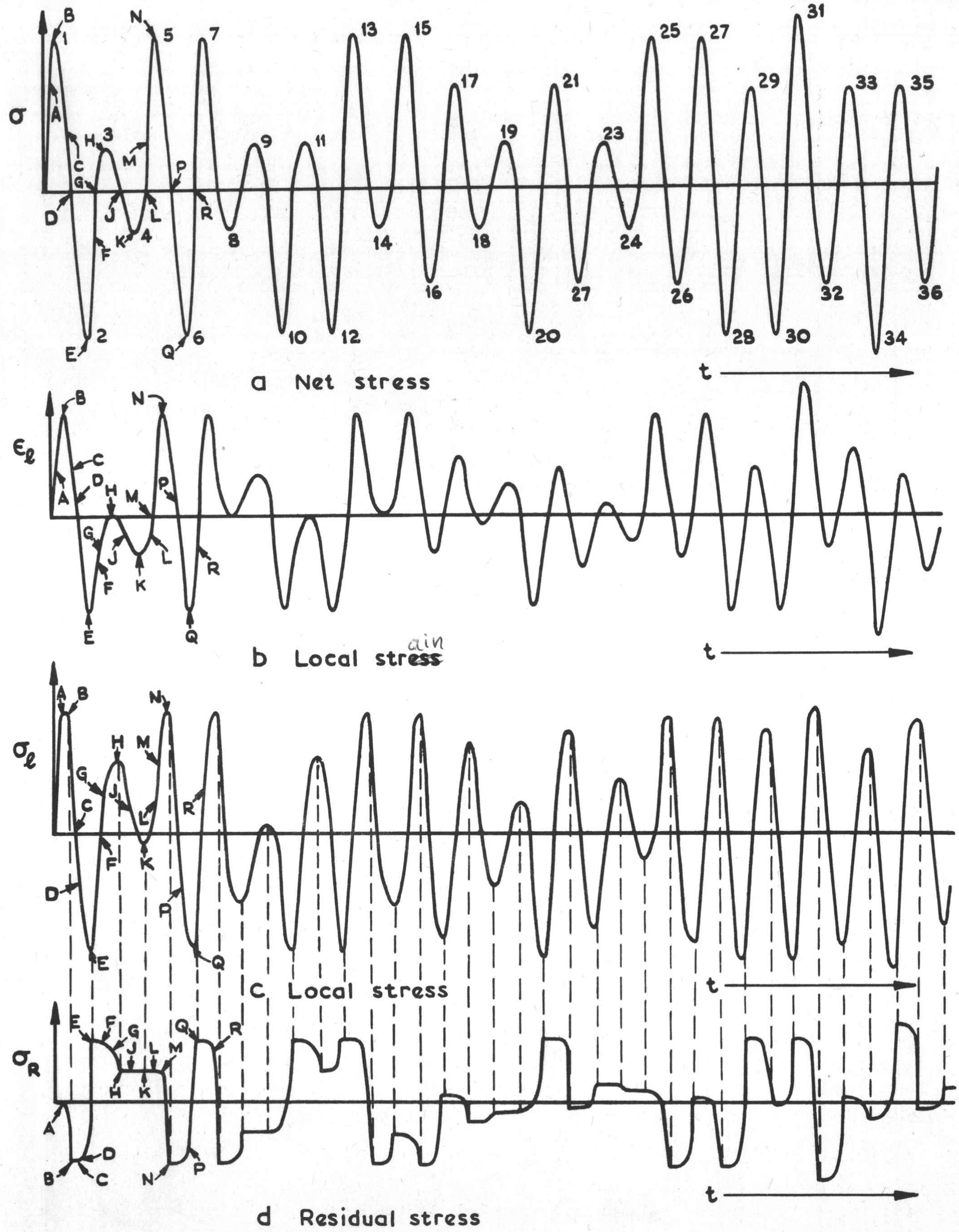


Fig.22a-d Stress and strain histories in notched specimen (sequence I)

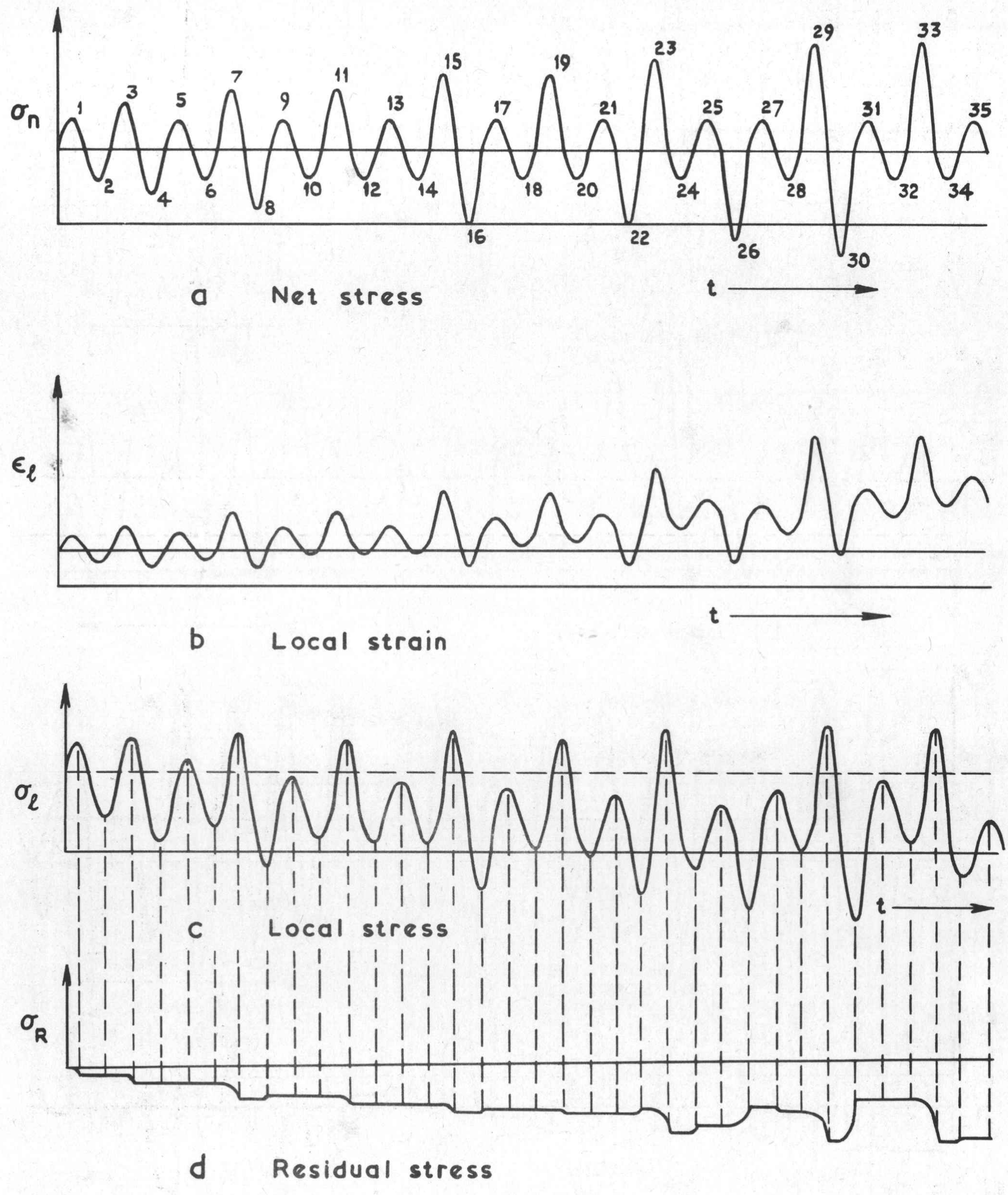


Fig. 23a–d Stress and strain histories in notched specimen (sequence 2)

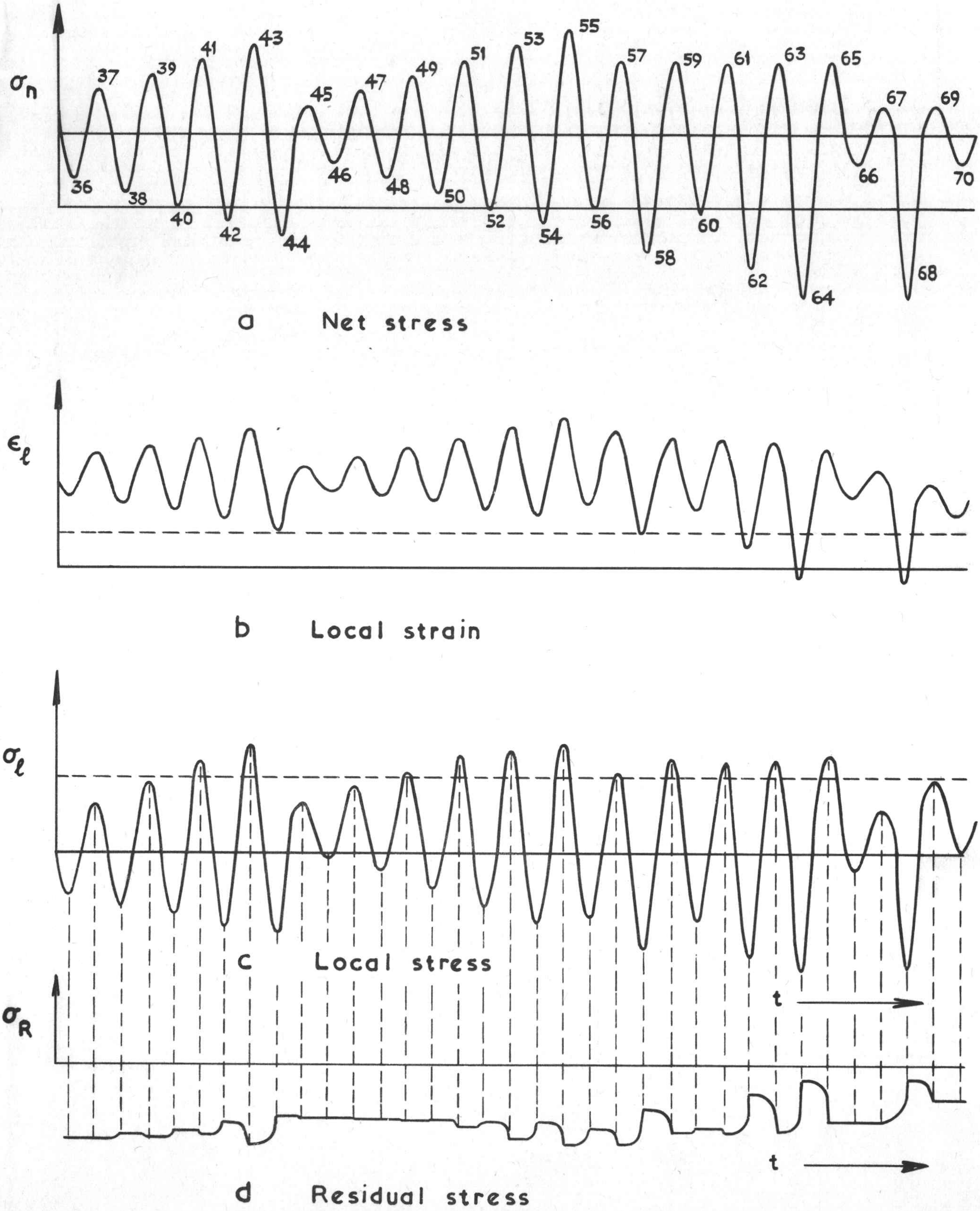


Fig. 24 a-d Stress and strain histories in notched specimen — sequence 2 (contd)