R. & M. No. 3798

R. & M. No. 3798

PROCUREMENT EXECUTIVE MINISTRY OF DEFENCE

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Effects of Heat on Fatigue in Aircraft Structure

By J. R. HEATH-SMITH AND F. E. KIDDLE
Structures Department, R.A.E., Farnborough, Hants.

LONDON: HER MAJESTY'S STATIONERY OFFICE
1977
£4 net

Effects of Heat on Fatigue in Aircraft Structure

By J. R. HEATH-SMITH AND F. E. KIDDLE
Structures Department, R.A.E., Farnborough, Hants.

Reports and Memoranda No. 3798*
December, 1975

Summary

This paper reviews the understanding in the UK of the effects of kinetic heating on fatigue in aluminium alloy aircraft structure. It describes how heating can affect subsequent fatigue at ambient temperature by softening strain-hardened material and redistributing local stress by creep. It also discusses the effect on structural joints of the relaxation of clamping pressure and interference fit, and the curing of interfay compound. Tests on structural elements are described which show that, under representative load-temperature sequences with a maximum temperature of 100°C, effects on life can range between reduction and improvement by a factor of 2, depending on circumstances.

The substance of this paper was presented at the ICAF Symposium held in Lausanne in June 1975 *on "Problems with Fatigue in Aircraft"*.

---

* Replaces R.A.E. Technical Report 75131—A.R.C. 36 724

LIST OF CONTENTS

1. Introduction

Development of a Mach 2 supersonic transport in aluminium alloy has stimulated a great deal of research into the effects of kinetic heating on structural fatigue. Compared with other spheres of elevated temperature engineering the level of heating is quite modest—the general operating temperature is encountered every day when water is boiled in an aluminium saucepan. In fact the total exposure to heat during the service life has little effect on static properties and causes little overall creep. Nevertheless there are two aspects to kinetic heating which are significant to structural fatigue. The first of these is the heating up and cooling down of the aircraft surface during each supersonic flight which induces a thermal stress cycle contributing to the general fatigue damage and critically affecting design at some locations. The second aspect of the problem is of general importance to the airframe and concerns the effect of periodic heating on the progressive accumulation of fatigue damage at ambient temperature under the usual loading actions experienced by all transport aircraft. To investigate this second aspect an extensive programme of work has been carried out for fifteen years or so and is still continuing. Although this work has yet to be completed our understanding of heating effects in aluminium alloy structures is well enough founded to warrant review at this time.

The first part of the paper outlines the main experimental observations on simple specimens under simple testing conditions. The implications of these results to the service situation are then discussed and finally results are presented from tests under sequences of load and temperature representing the repetitive nature of service conditions.

2. Basic Experimental Observations

2.1. Fatigue at Elevated Temperature

It is known[1,2,3] that for plain specimens the alternating fatigue strength of a large number of fully-aged aluminium alloys reduces progressively with increasing temperature due to the combined action of overageing and temperature (Fig. 1a). To extend this information to the structural situation, tests were conducted on notched and pinned lug specimens in a fully-aged aluminium alloy. The loading was of constant amplitude in fluctuating tension at 33 Hz and the effect of constant elevated temperature was investigated over the range 20°C to 300°C. The results[4] were presented at the ICAF Symposium in Rome, 1963, and showed that temperatures between about 100 and 150°C gave improvements in fatigue strength whereas at higher temperatures the strength dropped rapidly below the room temperature value until at 300°C the failure was due primarily to creep (Fig. 1b). By contrast with plain specimen behaviour, the relative improvement in the structural specimen behaviour between 100 and 150°C was thought to be associated with redistribution of local stress by yield and creep at elevated temperature which would result in a lower value of local mean stress and hence a better fatigue performance. It was assumed that at higher temperatures this beneficial effect was overcome by rapid overageing and the onset of creep damage. Whilst it was appreciated that the balance between beneficial and detrimental factors would possibly be sensitive to times of exposure it was nevertheless considered potentially important that a net gain in fatigue strength was possible at temperatures generally achieved over the structures of Mach 2 aircraft.

2.2. Fatigue after Heating

Attention was next turned to the effect of periods of heating on subsequent fatigue at room temperature. This case is of particular importance to supersonic transport aircraft which generally speaking are hot under steady load conditions and cold when the load is most variable. It was first ascertained[5,6] that for RR58 material, the fully-aged Al–2·5% Cu alloy used in Concorde, heating for up to 1000 h at 150°C and 30 000 h at 120°C with and without static loading had no significant effect on the room temperature static properties and that 1000 h at 150°C had little effect on the fatigue performance of plain specimens, indicating that the accumulation of overageing or creep damage in the plain material was not significant. A programme of fatigue testing was also started to study the effect of heating at temperatures from 100 to 150°C on the fatigue performance in fluctuating tension of simple structural elements at ambient temperature. The lower value is the maximum temperature which is reached generally over the Concorde in service and the higher temperature is a value unlikely to be exceeded even in accelerated full-scale testing.

The single period of heating applied in these tests varied from as little as 1 hour to represent a single cruise period to as much as 20 000 hours to represent the total exposure during the service life. During heating, the load on the specimen was maintained at a steady value of tension, zero load or compression to simulate conditions at different parts of the structure during the cruise. The range of structural elements included centrally notched specimens with two values of stress concentration and pinned and clamped forms of lug specimen. Four fully-aged Al–Cu alloys were selected, of which two were commonly used alloys and two were particularly suited to elevated temperature applications.

The principle was to establish fatigue performance by continuous fatigue tests to failure at room temperature and then to interrupt similar tests at some stage for a single period of heating in order to determine the effect of overall fatigue life. It was considered that this approach, employing only one period of heating, could reveal an effect on the fatigue characteristics of the material as a whole or specific effects on the initiation and early growth of cracks but would be unlikely to disclose changes in the material immediately surrounding the tip of an advancing crack, once it were long enough to pass quickly through the affected region.

In broad perspective the results[7] of this programme present a fairly simple picture compatible with the behaviour observed in the tests at constant elevated temperature described earlier. When heat was applied to an unloaded specimen the subsequent fatigue performance at ambient temperature was reduced. However, the application of tension during heating was beneficial so that the performance was less reduced than by heating alone and could even show a net improvement over the unheated specimens. In contrast, compression during heating was detrimental to subsequent fatigue in fluctuating tension. The simplest interpretation of the observations is that:

(a) heat causes a change in the metallurgical condition of the material which is deleterious to fatigue performance and

(b) creep (and sometimes elevated temperature yield) under the applied load gives a relative improvement (tensile creep) or further reduction (compressive creep) in the performance by modifying the local mean stress.

For the four materials tested the behaviour was similar but the magnitude of the effects differed to some extent. The behaviour of the different types of specimen will now be discussed in some detail.

2.2.1. Notched Specimens

The notched specimens were more sensitive to heating than the specimens with fretting and it is instructive to study a typical result for a notched specimen in some detail. Fig. 2 shows a particular example[8] of the effect on endurance of interrupting the fatigue loading at some stage and applying heat without load on the specimen. It is seen that the reduction in endurance is greatest when heat is applied at the beginning of the test and that the reduction diminishes as the heating is delayed to later stages, becoming negligible in the last stage of the life. This suggests that crack initiation is speeded up by heating and this idea is strengthened by the impression that scatter in endurance is considerably reduced for the heated specimens. Further corroboration comes from examination of the fracture surfaces of which Fig. 3a is a typical example. It was possible to observe discrete origins of cracking at various positions along the bore of the hole as indicated. By counting the number of origins on each fracture surface it was found that reduction in life after heating was associated with an increased number of origins (Fig. 3b), suggesting an increased susceptibility to crack initiation. By fractographic and hardness surveys it was shown[9] that the change in crack initiation characteristics was connected with changes in the microstructure of the surface layer of the material during heating. It was found that the operation of drilling and reaming the hole had left a layer of work-hardened material at the surface to a depth of about 40 μm in which grain boundaries and precipitates were destroyed. Micro-hardness measurements were made on a tapered section through this layer and Fig. 4 shows that the hardness at the surface was about twice the value for the interior material and decreased progressively through the layer. It was apparent that this layer possessed a high resistance to crack initiation as cracks normally originated just below the layer. After heating however, the surface layer had recovered to normal hardness and contained coarse precipitation and the fatigue cracks initiated right at the surface. The possibility that the phenomenon depends on the relaxation of beneficial residual stresses induced in the surface during machining can be discounted, as reduction in endurance was observed[10] under loading of sufficient severity to induce residual stresses much larger than those likely to result from manufacture. The relaxation of residual stress during heating is a separate phenomenon of importance and is discussed later. From the foregoing discussion it is apparent that heating reduced the fatigue life in these experiments, not by producing significant changes in the material as a whole, but by reducing the inherent fatigue resistance of the machine hardened surface.

The effect of this surface softening was studied over a range of heating times and temperatures with remarkable results. Fig. 5 shows for a notched specimen the effect of preheating on the endurance at one level of constant amplitude loading; the mean endurance in this particular case was reduced to 66 per cent of its normal value regardless of temperature over the range 110 to 150°C and regardless of the diversity of exposure times used, e.g. from 3 h to 20 000 h at 120°C. Below 110°C the effect was less pronounced. The apparent rapidity with which fatigue initiation resistance was lost at these moderate temperatures is of particular significance to military aircraft which are subjected to only brief periods of kinetic heating and also to structure which is exposed to only moderate engine heat.

In the USSR, investigations have been conducted, in connection with the Tu 144 aircraft, on the effect of preheating AK4–1–T1 material, an artificially aged aluminium alloy. Available information[11] on the effect of preheating at 150°C is confined to rotating bending tests on circumferentially notched specimens of $K_t = 2{\cdot}6$. It is difficult to relate these results to those already described as the AK4 material was less than fully aged and the fatigue life doubled after a few hours at 150°C. However, it is worth noting that longer periods of heating caused progressive reduction in life; after 3000 h the life was reduced to 40 per cent of the peak value.

Having discussed the effect of heat on an unloaded specimen it is appropriate to consider the more general situation where the material is under steady stress during heating. Fig. 6 gives two examples of the dependence of endurance on the level of steady stress during preheating of the specimen. Endurance is displayed as a percentage of the mean endurance of an unheated specimen and is plotted against the level of stress during heating. The upper curve[12] is for a moderate stress concentration under constant amplitude loading. At a steady stress of zero during heating the curve shows the reduced endurance due to surface softening. It is seen that a compressive stress reduced the life still further but that a tensile stress tended to restore the endurance and at the higher values gave an improvement in life over that of the unheated specimen. By contrast the lower curve[10], which was obtained for a more severe stress concentration under a random sequence of mixed load levels, shows a constant loss of endurance over the range of stress levels applied during the heating.

The behaviour in these two series of tests can be explained satisfactorily from consideration of the action of creep during the heating period in redistributing stress across the net section. Considering first the moderate stress concentration under constant amplitude loading, Fig. 7 shows diagrammatically the local stress–strain changes at the root of the notch during the heating under compression, zero load and tension respectively. In Fig. 7a compression is applied (OA), the specimen is heated and the local stress relaxes (AB) by an amount depending on the time available for creep redistribution: it is assumed in the diagram that relaxation is substantially completed (B). The specimen is then cooled and unloaded to point C where the specimen has a tensile residual stress due to creep. On starting the fatigue test the application of mean load takes the local material into tensile yield at point D and the first peak of the alternating load yields it further to point E. Thereafter the fatigue loading gives elastic movement along line EF about the mean position G. In Fig. 7b the specimen is heated whilst unloaded at point O and after cooling the application of mean load causes elastic movement to point H, the first peak load causes yielding to point J and thereafter the material deforms elastically along the line JK about the mean point L. In the last case, Fig. 7c, the specimen is loaded in tension to point M and is heated for a period during which the local material relaxes to point N. After cooling, the specimen is unloaded and the local material has a residual compressive stress (OP). Due to this residual stress the specimen does not reach tensile yield on application of the mean load (S) and the peak load (Q) and during fatigue the local material deforms elastically along line QR about mean point S. In comparing these three histories it is apparent that the effect of compressive creep is to raise the local mean stress slightly and that the effect of tensile creep is to reduce the local mean stress considerably. In view of the sensitivity of fatigue in aluminium alloy to mean stress, the above changes in local mean stress would affect initiation and early crack growth within the residual stress field of the notch and this would account qualitatively for the variation in endurance observed in the upper curve of Fig. 6.

It remains to explain the lower curve which shows no effect from the stress level during heating for the more severe stress concentration under the random spectrum of loads. Figs. 8a, b and c show diagrammatically the local stress–strain changes for this case and are analogous to Figs. 7a, b and c which were described in detail above. The salient feature of Fig. 8 is that the combination of high stress concentration and the occasional high level of stress cycle in the loading spectrum results in tensile yielding regardless of the effect of creep redistribution. Thus even in the case when creep induces a residual tensile stress this is replaced by a residual compressive stress as soon as a moderately high peak tensile stress occurs in the subsequent fatigue loading, and it can be seen in Figs. 8a, b and c that the mean stress during fatigue is sensibly the same. For this reason the lower curve of Fig. 6 is uninfluenced by the effect of heat on residual stress and shows only a constant reduction in endurance due to surface softening, in this case to 23 per cent of the unheated value.

From these two examples it is seen that the effect of creep redistribution on endurance depends critically on the relative magnitudes of the creep and fatigue stresses, as the residual stresses induced by creep may be subsequently modified by yielding under fatigue loading. Another illustration of creep redistribution is provided by Fig. 9 which shows the S–N curves for a notched specimen in three conditions: without heating, after heating at zero load and after heating under tensile load. The first point to note is that the S–N curve is displaced to the left by heating at zero load which causes surface softening. However, when tension is applied during heating the curve is displaced considerably to the right by the reduction in local mean stress by creep redistribution. The improvement is greatest at the low alternating stress levels and diminishes as the curves for heating with and without load converge at a high level of alternating stress. Although the longer lives after creep are a consequence of the reduced local mean stress, the specimens without the benefit of creep redistribution also experience a reduction in local mean stress when the peak stress of the fatigue loading causes yielding. Thus with increasing alternating stress the benefit of creep diminishes and is superseded by the effect of yielding at the stress level where the two curves converge.

In assessing the influence of creep in a practical situation one important consideration is the rate at which redistribution occurs. In the example just discussed the exposure was comparatively severe (124 MN m^{-2} for 1000 h at 150°C) and the fatigue behaviour is compatible with virtually complete redistribution. However, it is known that significant redistribution takes place rapidly as the upper curve in Fig. 6 was the result of only 3 hours at 150°C. At lower temperatures down to 100°C there is evidence of significant creep effect after long exposures and it is a reasonable assumption that initial redistribution is comparatively rapid at these temperatures also. It is relevant that extremely rapid creep redistribution effects on fatigue have been reported[13] for Ti 8–1–1 material.

To sum up, two major effects of heat have been seen in notched specimens: the softening of machined surfaces making them more susceptible to crack initiation, and the modification of local stress by creep which may have a beneficial or detrimental effect on crack initiation and early growth depending on the levels of the creep and fatigue stresses.

2.2.2 Pinned Lug Specimens

The pinned lug specimen was less sensitive to heat than the notched specimen. In particular, heating without load gave a comparatively small reduction in endurance. This is understandable because in these specimens fretting occurred between unlubricated metal surfaces so that initiation was comparatively rapid and changes in surface condition would not greatly affect the endurance. However, the effect of heating with load applied was significant and the pinned lug specimen displayed the influence of creep redistribution already observed in the notched specimens but to a lesser degree. Presumably although crack initiation was rapid the residual stress induced by creep influenced the early crack growth, which remained within the residual stress field for a substantial proportion of the total endurance. It is concluded that for specimens in which fretting influences the crack initiation the effect of heat on surface condition is relatively unimportant but that the redistribution of stress by creep influences early crack growth within the residual stress field.

2.2.3. Clamped Joints

A typical clamped joint in aircraft structure contains a complexity of features which are likely to be sensitive to heat. Some idea of the importance of two of these factors, stress concentration and fretting, has already been gained from the study of notched and lug specimens. However, in a typical joint, the influence of stress concentration and fretting is suppressed by the following means:

(a) Clamping is applied to the faces of the joint by the fasteners in order that load will be transferred by friction thus reducing the load transmitted by the fasteners.
(b) Interfay material is used to separate the metal surfaces and prevent fretting.
(c) Interference fit fasteners are used to reduce the fatigue loading and fretting amplitude at the holes.

Tests on several types of clamped joint have given some indication of the influence of these factors in fatigue-heat interaction.

Tension in a fastener will restrict the load transmitted in bearing provided there is adequate friction and rigidity between the faces of the joint. Tests[14] of bare metal clamped joints, in which clearance steel bolts were initially tensioned to a core stress of 60 per cent ultimate, showed that bolt tension was unaffected by fatigue loading but was reduced by 40 per cent during heating for 1000 hours at 150°C due to compressive creep in the aluminium centre plate. Although in this particular specimen the metal/metal friction was still adequate to transmit the entire fatigue loading by friction, it is possible that for typical joints, the reduced clamping would result in more load being transmitted in bearing, with an adverse effect on performance.

Similar specimens were used to examine the effect of introducing primer and an interfay of fluorocarbon polymer material and it was found[15] that heating improved the performance considerably. To put this improvement in perspective, Fig. 10 shows the S–N curves for various test conditions. The lowest curve is for the unclamped joint, i.e. a pin-loaded lug, tested without heating, and the next higher curve shows the improvement from applying clamping pressure and introducing a layer of interfay, not bonded to the joint.

Further improvement is shown when a bonded form of interfay was used which improved load transfer between the faces. The next higher pair of curves show the improvement in the clamped, bonded joint from preheating at 120°C for 1000 h and 20 000 h respectively. As failure was in all cases through the net section at the hole, then presumably the benefit of clamping derived from a reduction in the proportion of load transmitted in bearing. Transmission of load to the fastener was undoubtedly governed by the degree of slip permitted by the interfay; the difference in performance with bonded and unbonded interfay suggests that slip in the joint depends on both the rigidity of the interfay and its adherence to the joint faces. Evidence that the interfay was considerably affected by heating comes from tests to compare the shear strength of bonded interfay in joints which had been stored for 20 000 h and in joints which were heated for times up to 20 000 h at temperatures from 100 to 150°C. By removing the bolts and testing the shear strength of the bonding it was found that on average heating had improved the strength tenfold. In further fatigue tests at a higher level of clamping, failures were predominately from fretting between joint faces and again the endurance was improved by heating, which suggests in this case a reduction in fretting amplitude due to heating of the interfay. From the above series of tests it is concluded that the improvement in the performance of clamped joints after heating was largely influenced by curing of the interfay to give better adhesion and stiffness.

The influence of interference fit fasteners was studied[16] in tests of small riveted joints to compare heating effects for four different types of rivet. Before heating, the S–N curves for the different joints showed an order of merit which could be associated qualitatively with the degree of interference induced by riveting; the best S–N curve corresponded with the rivet of highest interference. After heating at 150°C the best performance was little affected but the lowest performance was appreciably improved as shown in Fig. 11. From various considerations it was deduced that both beneficial and detrimental factors were involved: whereas there was a tendency for all types of joint to be improved, possibly by such factors as interfay curing and reduction of loading irregularity between fasteners by creep relaxation, there was additionally a loss of performance due to the relaxation of interference which was most pronounced for fasteners with high interference. Thus improvement was observed in the joint with least interference at the lower boundary of the diagram but was outweighed by loss of interference in the joint at the upper boundary.

From the above discussion it is seen that heating can have various effects, both beneficial and detrimental, on the fatigue performance of typical joints. On the debit side; if anti-fretting measures are effective, damage initiation may be hastened by loss of surface hardness as observed for notched specimens; if clamping is reduced by creep more load may be transmitted to the fasteners where stress concentration is high; and if fastener interference is lost by creep the result is again a higher fatigue loading at the fasteners. Against these effects can be set certain advantages; curing of the interfay may improve load transmission between the faces of the joint; initial disparities between fastener loads will be rectified; and creep under tensile load will give favourable redistribution of local stress at fastener holes once interference stresses are lost.

2.2.4. Crack Propagation

Up to this point, discussion has been concerned primarily with effects on crack initiation and early crack growth within the residual stress field of the stress concentration, since no specific effect on crack propagation characteristics was detected on the simple structural elements tested.

In fact, crack propagation tests[17,18] on thin sheet specimens showed a tendency towards slightly slower crack rates if the material was preheated for 1000 h at 150°C, an exposure which did not cause significant overageing. Although the observed effect on overall crack propagation characteristics was small, there is the additional possibility that, once a crack is present, a period of heating could affect the limited zone of material at the crack tip which has been subjected to plastic strain, and could cause a significant but short-lived change in the subsequent crack rate. It can be envisaged for example that material at the crack tip could be affected in analogous manner to that observed for surface material at the point of initiation; the strain-hardened material in the plastic zone could be softened and the residual stress pattern could be modified by creep and by lowering of the yield stress at elevated temperature. Due to experimental difficulties little work has been done to examine directly the effect of heat on conditions at the crack tip. In one investigation[17] tests were interrupted at various crack lengths for the application of heat without load but no transitory effects on crack rate were observed immediately following the heating. However, the scope of these tests was limited and the negative result is far from conclusive as any effect may have been so localized that it was undetectable by conventional methods of crack rate measurement, and yet, if heat were applied frequently during propagation, could have significantly changed the average crack rate.

Mention should be made of information[18,19,20] from several sources on crack propagation at elevated temperature in a number of aluminium alloys. In all cases the effect of testing at 150°C was an appreciable reduction in crack rate, in one instance to one half of the rate at room temperature. It seems most likely that beneficial stress redistribution at the crack tip was responsible but it is not known to what extent this was due in these tests to creep or to the reduced yield stress at elevated temperature.

It is concluded from this limited evidence that the effect of prior heating on overall crack propagation characteristics is a slight tendency to slower crack rates. No transitory effects were detected at the crack tip following heating without load but elevated temperature tests suggest that creep redistribution at the crack tip may cause significant retardation.

3. Significance of Heating under Service Conditions

Having discussed the effects of single heating periods under relatively simple loading conditions it is necessary to consider the implications of this basic information to the practical situation in service when the fatigue loading and heating follow a flight-by-flight pattern. An important consideration is the observation made earlier that quite short periods of heating are effective in modifying the metallurgical condition and stress state of material at a stress concentration. It is possible therefore that heating periods of only one or two hours, which is a typical duration for the cruise phase of a supersonic transport, could bring about significant changes in those parts of the structure which reach a temperature of 100°C or more. It was suggested in the previous section that similar mechanisms may operate in the plastically deformed material ahead of the growing crack. Thus when heating is applied at frequent intervals during the life, the material at the immediate damage front will be modified repeatedly by heat as the damage progresses from initiation to failure.

The significance of creep redistribution at any structural location will depend critically on the magnitude and sequence of the fatigue loads, on the positioning of the heating period in this sequence, and on the level of nominal stress during heating. To examine the various possibilities for a simple stress concentration with no interference some examples of load temperature sequences will be considered representing conditions in wing, fuselage and fin structure.

3.1. Wing

Fig. 12 gives a generalised loading for the lower surface of the wing outboard of the undercarriage during several flight cycles, and represents the ground-air-ground cycle, random gust loading during the climb and descent, and random taxying loads during ground running. We will first consider the effect of this loading sequence on local stress level, neglecting for the moment the effect of heating. At stress levels typical for transport aircraft it is quite possible for local tensile yielding to occur under the larger peak gust loads say at point B. The consequent reduction in local mean stress level from A to C would reduce the subsequent rate of fatigue damage until the occurrence of a load reduction at point D, say, sufficient to cause local compressive yielding and raise the local mean stress at E during the next flight. This condition would substantially persist until some later flight when there next occurs a sufficiently large load to again cause local yielding. It will be appreciated therefore that local mean stress levels will be lowered and raised by turn depending on the operating stress levels and on the occurrence of occasional large peaks and troughs in the loading. It is a useful generalisation that very turbulent flights and heavy landings are comparatively rare and that therefore a beneficial reduction in local stress due to a high gust may persist for many flights before it is cancelled by a heavy landing. Similarly the effect of a heavy landing will persist, to the detriment of the fatigue performance, until the next large gust occurs. In this situation the occurrence of heating at a steady tensile stress during each cruise phase, as indicated by the broken line in Fig. 12, will be an additional factor in relaxing local mean stress. If the local stress is already at a reduced level there will be further reduction due to creep. If the local stress is high following a heavy landing it will be reduced by creep during the next flight without the usual delay before a high gust next occurs. Creep redistribution therefore appears to be beneficial in this situation. However, the converse is true of the upper surface of the wing which will experience a similar but inverted stress sequence and will suffer compressive creep during the cruise which will tend to emphasise the tensile fatigue during taxying.

The situation just discussed for the lower surface of the wing whilst useful for illustration, is not typical for Concorde because much of the lower surface is wetted by fuel and, due to convective cooling, will see little temperature rise. For those sections which do get hot the mean stress during the cruise will not necessarily be as portrayed in Fig. 12 but may be offset by compressive thermal stress due to local temperature gradient, and the benefit from creep redistribution will be reduced correspondingly.

3.2. Fuselage

The fuselage loading in Fig. 13 represents an upper surface location which is in tension on the ground and during flight. During the climb pressurisation builds up and heating occurs at the highest stress level during flight. Creep relaxation could be of considerable benefit to fatigue performance in this case. Thermal stresses will be significant on the lower surface of the fuselage close to the areas masked by the root of the wing, and the loading will be as shown in Fig. 14. The reduction in tension during the cruise will reduce the degree of creep benefit to be expected; however, this would be of no consequence if the tensile thermal stress following the cruise were sufficiently large to cause yielding, as indicated in the local stress–strain diagram.

3.3. Fin

The fin loading shown in Fig. 15 represents symmetrical gust and manoeuvre loads about zero load with heating periods at steady load during each cruise phase. Occasional loads high enough to cause local yield may vary the local mean stress to either side of zero and the periods of heating will tend to hasten the return of local mean stress to zero. Creep therefore has the effect of equalising damage rate each side of the fin, which may be of some benefit.

3.4. Possibility of Plastic Strain Cycling

In the cases considered above, creep relaxation whether beneficial or detrimental has been portrayed as having a persistent and progressive effect during the course of many flights on the residual stress state, being disturbed only occasionally by the occurrence of loads large enough to cause yielding in the opposite sense to the creep. It is nevertheless possible that situations will exist where a regular cycle of interaction will develop between creep and yield such that plastic strain cycling will occur during each flight cycle. In this event the influence of creep in modifying mean stress is at best short-lived and may be overshadowed by the damaging effect of cyclic plastic deformation. Fig. 16a illustrates a situation in which the mean load level alternates between tension and compression during each flight cycle and is fairly equally disposed about zero. Heating will relax local stress from A to B, as a consequence of which the reversal of load on landing will cause compressive yield to C. At the commencement of the next flight the local stress will return to A to repeat the cycle. An analogous situation is shown in Fig. 16b for structure which is in compression during the cruise.

4. Tests under Representative Load-Temperature Conditions

Preceding sections have discussed simple fatigue-heat interactions in various structural elements and the implications of the observed effects to behaviour under the complex sequences of load and temperature encountered in service. This section will consider the results of tests in which the applied load and temperature sequences simulate many of the features of service conditions.

4.1. Crack Propagation

It has been postulated that the repeated application of heat during crack propagation will affect the region at the crack tip in two ways: by softening the strain-hardened material and by creep relaxation of the residual stress field. Fig. 17 presents the results[21] of tests on clad sheet with a central crack starter, under various repeated sequences of load and temperature. In Fig. 17a heat was applied at low stress when the crack tip material was under residual compression. Relaxation of this residual stress would be ineffectual however, as heating was always followed by application of peak stress which would restore the residual compression. Therefore the only heating effect to be expected is softening of the crack tip material but this did not materialise as similar crack rates were observed at maximum temperatures of 20, 100 and 130°C. In the comparable tests of Fig. 17b in which heat was applied at peak stress, creep relaxation would be expected to retard the crack growth and this is confirmed by the results in which the crack rates are halved by heating at 100 and 130°C. In Fig. 17c the load sequence is similar but includes a higher peak stress immediately following the heating period to represent a severe thermal stress situation. As for Fig. 17a the relaxation of residual compression would be ineffective but in contrast the softening mechanism appears to be very effective as the crack rates with heating at 100 and 130°C are in this case 2 to 4 times higher than in the room temperature tests. In the comparable test of Fig. 17d heat is applied at an intermediate stress level and it could be expected that creep would relax much of the plastic zone and give some degree of crack retardation. This is borne out by the result which shows that the large increases in crack rate due to softening were moderated by creep relaxation to about 1·5 times the room temperature value.

It is seen from the above results that significant changes in crack growth rate can arise from repeated heating: it is deduced that softening of crack tip material increases crack rate at high levels of peak stress, and tensile creep enhances residual stress and hence reduces crack rate.

4.2. Crack Initiation and Early Growth

A series of tests[21] were carried out on sheet specimens 254 mm wide to study crack initiation at a central hole of 9·5 mm diameter and subsequent growth to a length of 2 mm from the edge of the hole. As the material was clad, initiation and early crack growth took place within the cladding which, being soft and unable to support significant residual stress, was unlikely to be affected by heat. Once the crack reached the core material, softening and creep redistribution may have had some effect. Fig. 18 describes three series of tests. In Fig. 18a heat will relax the residual compression at the crack tip but this will be restored by the peak stress immediately following heating. Softening at the crack tip will not be very effective because the peak stress is only moderate. Accordingly only a slight reduction in life was observed for this test condition. Fig. 18b is a comparable case in which heat was applied at peak stress and the resulting increase in residual compressive stress by creep was responsible for the net improvement in life observed. Fig. 18c introduced a high peak stress which had the dual effect of reducing the benefit of creep relaxation and increasing the damaging effect of crack tip softening. The result was therefore a substantial reduction in life from heating.

4.3. Endurance of Notched Specimens

Fig. 19 describes a series of tests[22] to failure on notched specimens with a central hole, machined from plate material. The test condition of Fig. 19a in which heat was applied at low stress gave a reduction in life which can be attributed to softening of the surface of the hole and the crack tip and possibly to some contribution from creep relaxation of residual compression which is fully restored by the peak stress only in every thirtieth flight of the loading sequence. In the comparable test of Fig. 19b heat is applied at an intermediate stress level and the residual compression is sufficiently enhanced by creep to give a net improvement in endurance.

4.4. Endurance of Riveted Joints

Fig. 20 describes tests on two types of riveted joint. Fig. 20a refers to a joint[23] in clad material with interfay and aluminium countersunk rivets, which failed through the rivet holes. Peak stress was too low to cause yield at the holes and once a crack formed any relaxation of the residual compression at the crack tip would be restored immediately after heating. Softening at the crack tip probably had little effect at the moderate stress levels. The observed life with heating was within ± 20 per cent of the life at room temperature which suggests that any effects on clamping, interfay, or fastener interference were small. This result can be compared with Fig. 20b in which heat was applied at the peak stress and gave a net improvement in life by inducing residual compression. Figs. 20c and 20d refer to a joint[22] in machined material again containing interfay but with Monel rivets. If the results of these tests are compared with identical tests on notched specimens already described in Figs. 19a and b it is seen that heating is generally more detrimental to the riveted joint. It is tentatively suggested that the low performance of the joint is associated with reductions in the high levels of clamping and interference achieved with Monel rivets.

4.5. General Observations

The foregoing account of observed behaviour under representative load-temperature sequences is not yet complete as testing programmes and analysis of results continue to provide information on other forms of material and variants of the load-temperature sequence. The available results are however, substantially in accord with the behaviour suggested by the basic experimental observations described in Section 2, and are thought to provide a good general indication of the effects of intermittent heating at these temperatures on the structural fatigue performance of fully hardened aluminium–copper alloys. In particular the results appear to bear out the suggestion that the softening by heat and the stress redistribution by creep which were observed to influence crack initiation and early crack growth, are also effective at the tip of a growing crack. There is less certainty about the importance of changes in the parameters encountered in joints: clamping, interfay and interference. There is however, some evidence to suggest that reduction in clamping and interference could significantly reduce performance.

A summary of the effects of intermittent heating at 100°C, the general level of temperature on the surface of Concorde during cruise, is given in Fig. 21. The four generalized forms of repeated load-temperature sequence are characterized by:

A High peak stress and heat at zero stress
B High peak stress and heat at an intermediate stress
C Moderate peak stress and heat at zero stress
D Moderate peak stress and heat at peak stress.

The effect of heating is expressed as a factor applied to the life without heat. In the upper half of the table there is a general tendency for life reduction due to heating. An exception is the notch in machined material; a substantial proportion of the life is spent in crack initiation which, for this temperature, is not particularly sensitive to heating without load (see Fig. 5). In all cases performance is better under sequence B than under sequence A due to some benefit from creep redistribution. In the lower half of the table, where peak stresses are moderate, heating without load is not deleterious and improvements in performance arise either from creep redistribution or, more probably for the riveted joints, from curing of interfay compound. Overall, these observations on effects of intermittent heating at 100°C show changes in fatigue life ranging between reduction and improvement by a factor of 2.

5. Conclusions

Consideration of available data on the effects of heating at temperatures in the range 100 to 150°C on the fatigue performance of fully-aged aluminium alloy structure leads to the following conclusions:

(1) Strain-hardened material at machined surfaces and at the crack tip is appreciably softened by heating exposures of a few hours duration and is more vulnerable to subsequent fatigue at ambient temperature.

(2) During periods of heating of a few hours duration, local stress at geometrical stress concentrations and at crack tips is redistributed by creep and the subsequent fatigue performance at ambient temperature is improved or reduced dependent on the local stress being less or more tensile than before.

(3) Consideration of stress and temperature conditions at various locations in a typical airframe suggests that over much of the structure the effect of heating depends on the balance between the benefit of tensile creep redistribution and the loss of performance due to softening.

(4) However, additional factors may be important in joints: detrimental effects from reduction in clamping and interference due to creep, and beneficial effects from the redistribution of load between fasteners and from curing of interfay compound.

(5) Under representative load-temperature sequences with heating at 100°C a variety of tests on structural elements have shown effects on fatigue life commonly ranging between reduction and improvement by a factor of 2, depending on circumstances.

REFERENCES

No.	*Author(s)*	*Title, etc*
1	R. G. Ward	A comparison of the fatigue properties of the high strength Al–Cu–Zn alloys with the Al–Cu duralumin type alloys. R.A.E. Technical Note Met 244 (1956).
2	P. H. Frith	Properties of wrought and cast aluminium alloys at atmospheric and elevated temperatures. Bristol Aeroplane Co. Report to MOS.
3	Thorpe, Ridley, and Tremain	The mechanical properties of some wrought and cast aluminium alloys at elevated temperatures. *J. Inst. Metals*, Vol. 77, pp. 111–140 (1950).
4	J. R. Heath-Smith	Fatigue strength at elevated temperature of L65 aluminium alloy notched and lug specimens. *Current Aeronautical Fatigue Problems.* J. Schijve, J. R. Heath-Smith and E. R. Welbourne, Eds., Pergamon Press, London, pp. 103–130 (1965).
5	M. S. Binning	Direct stress fatigue tests on DTD5070A, BSL73 and 2024–T81 sheets. R.A.E. Technical Report 70221 (1970).
6	M. F. Day	Residual tensile properties of DTD5070A, BSL73 and Alclad 2024–T81 sheets after long time creep tests in the temperature range 100 to 150°C. Unpublished MOD(PE) work.
7	J. R. Heath-Smith and F. E. Kiddle	Effect of interrupting fatigue by periods of heat for aluminum alloy structural elements. *Fatigue at Elevated Temperatures.* A. E. Carden, A. J. McEvily and C. H. Wells, Eds., ASTM, STP 520, pp. 500–511 (1973).
8	F. E. Kiddle	Effect of interrupting fatigue by a period of heat for structural elements in three Al-Cu alloys. Unpublished MOD(PE) work.
9	P. J. E. Forsyth	The microstructural changes that drilling and reaming can cause in the bore of holes in DTD 5014 (RR58 extrusions) and the effects of subsequent heating. Aircr. Engng, Vol. 44, pp. 20–23, November 1972.
10	J. R. Heath-Smith and Judy E. Aplin	The effect of an application of heat on the fatigue performance under random loading of a notched specimen of DTD 5014 (RR58) material. A.R.C. C.P. No. 1221 (1972).
11	A. V. Vorob'ev, S. I. Ol'kin and V. N. Stebenev	The influence of prior creep on the fatigue strength of AK4–1–T1 alloy. Uchenye Zapiski TsAGI Vol. 3, (2), pp. 120–126 (1972). Translated in R.A.E. Library Translation 1836 (1975).
12	F. E. Kiddle	Influence of prior heat and creep on fatigue in structural elements of DTD 5014 (RR58) aluminium alloy. R.A.E. Technical Report 76094 (1976).
13	L. A. Imig	Effect of initial loads and of moderately elevated temperature on the room-temperature fatigue life of Ti–8Al–1Mo–1V

REFERENCES (concluded)

No.	*Author(s)*	*Title, etc.*
		titanium alloy sheet. NASA Technical Note D–4061 (1967).
14	J. R. Heath-Smith and F. E. Kiddle	Influence of ageing and creep on fatigue of structural elements in an Al6% Cu alloy. *Thermal and High Strain Fatigue.* The Metals and Metallurgy Trust, pp. 391–415 (1967).
15	F. E. Kiddle	Fatigue strength before and after heating of pinned and clamped lugs in RR58 plate and extruded material. Unpublished MOD(PE) work.
16	F. E. Kiddle	Fatigue strength before and after heating of DTD 5070A lap joints with solid rivets and special rivet fasteners. Unpublished MOD(PE) work.
17	F. E. Kiddle	The influence of a single application of heat on fatigue crack propagation in DTD 5070A (RR58) aluminium alloy sheet. A.R.C. C. P. No. 1272 (1974).
18	N. J. F. Gunn	Fatigue cracking rates and residual strengths of eight aluminium sheet alloys. R.A.E. Technical Report 64024 (1964).
19	R. Lachenaud	Fatigue strength and crack propagation in AU2GN alloy as a function of temperature and frequency. *Current Aeronautical Fatigue Problems*, Pergamon Press, pp. 77–101 (1965).
20	—	B.A.C. Report 69–76B-4023/1 Issue 2, B.A.C. (Filton) (1962).
21	F. E. Kiddle	Effect of interspersed periods of heating on fatigue crack initiation and propagation in CM001 (RR58) clad sheet. R.A.E. Technical Report 76092 (1976).
22	F. E. Kiddle	The fatigue life under flight by flight load and temperature sequences of notched and riveted joint specimens in CM003 (RR58) material. Unpublished MOD(PE) work.
23	F. E. Kiddle and R. J. Kite	The effect of interspersed heating on the fatigue endurance of aluminium alloy riveted lap joints in CM001 material. R.A.E. Technical Report 74052 (1974).

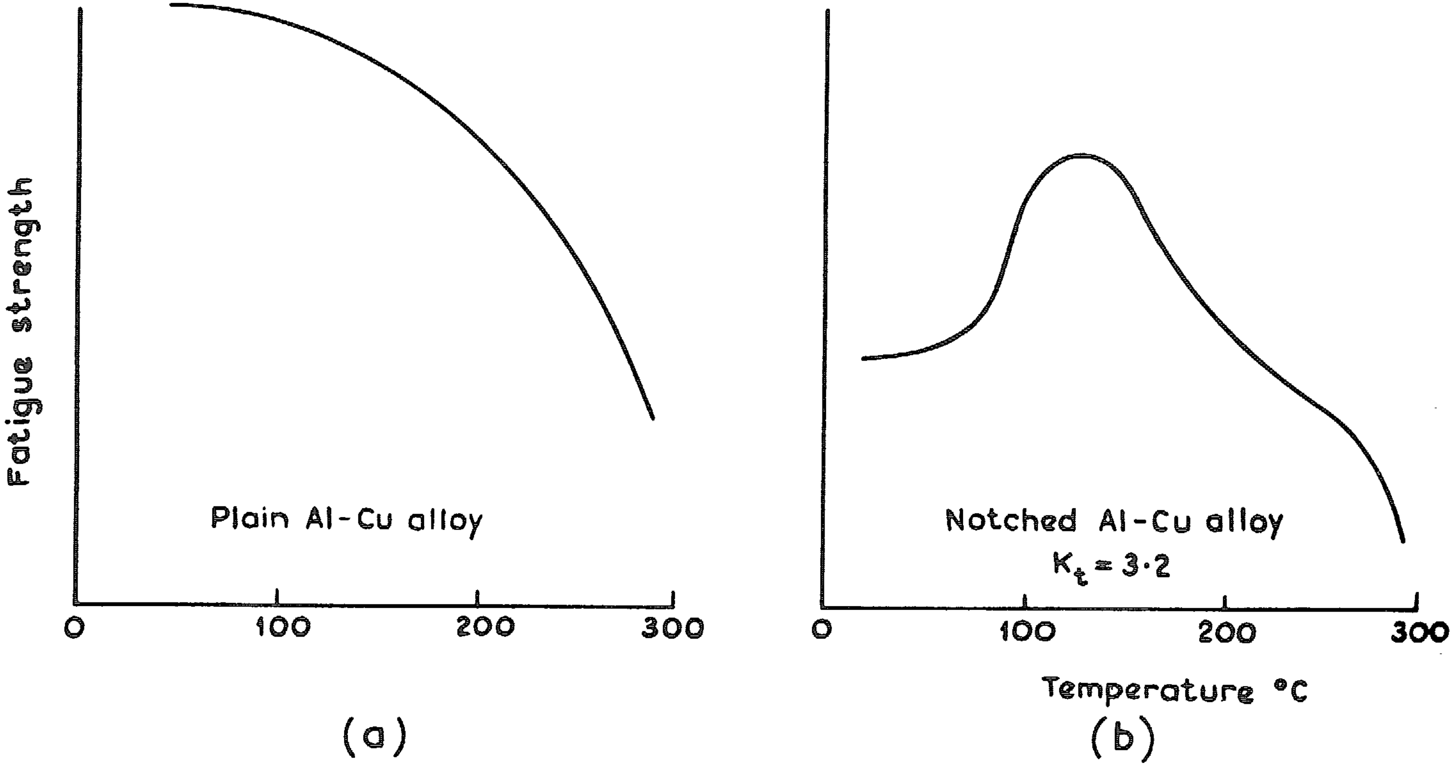


FIG. 1. Comparison of plain and notched fatigue at elevated temperature.

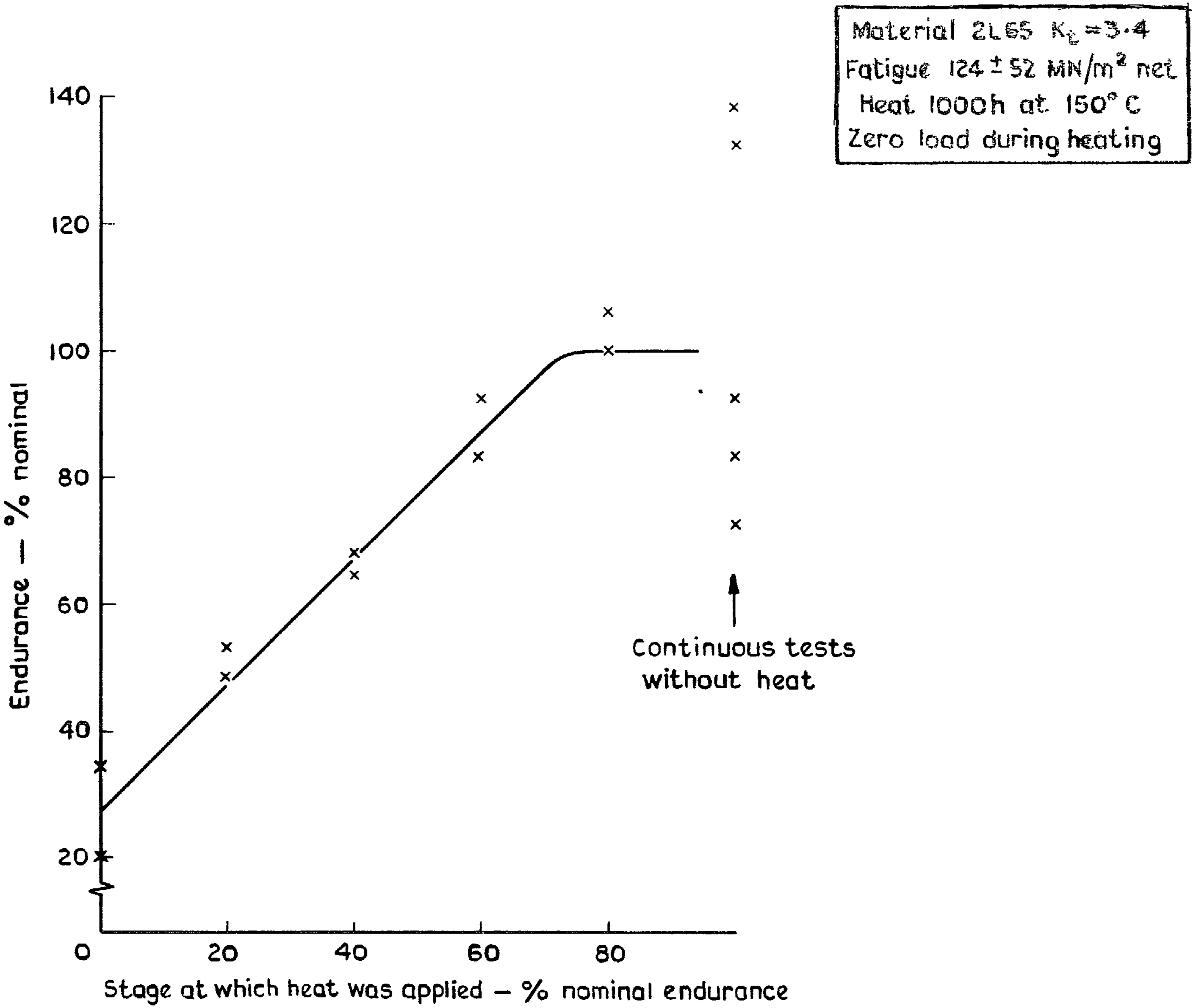
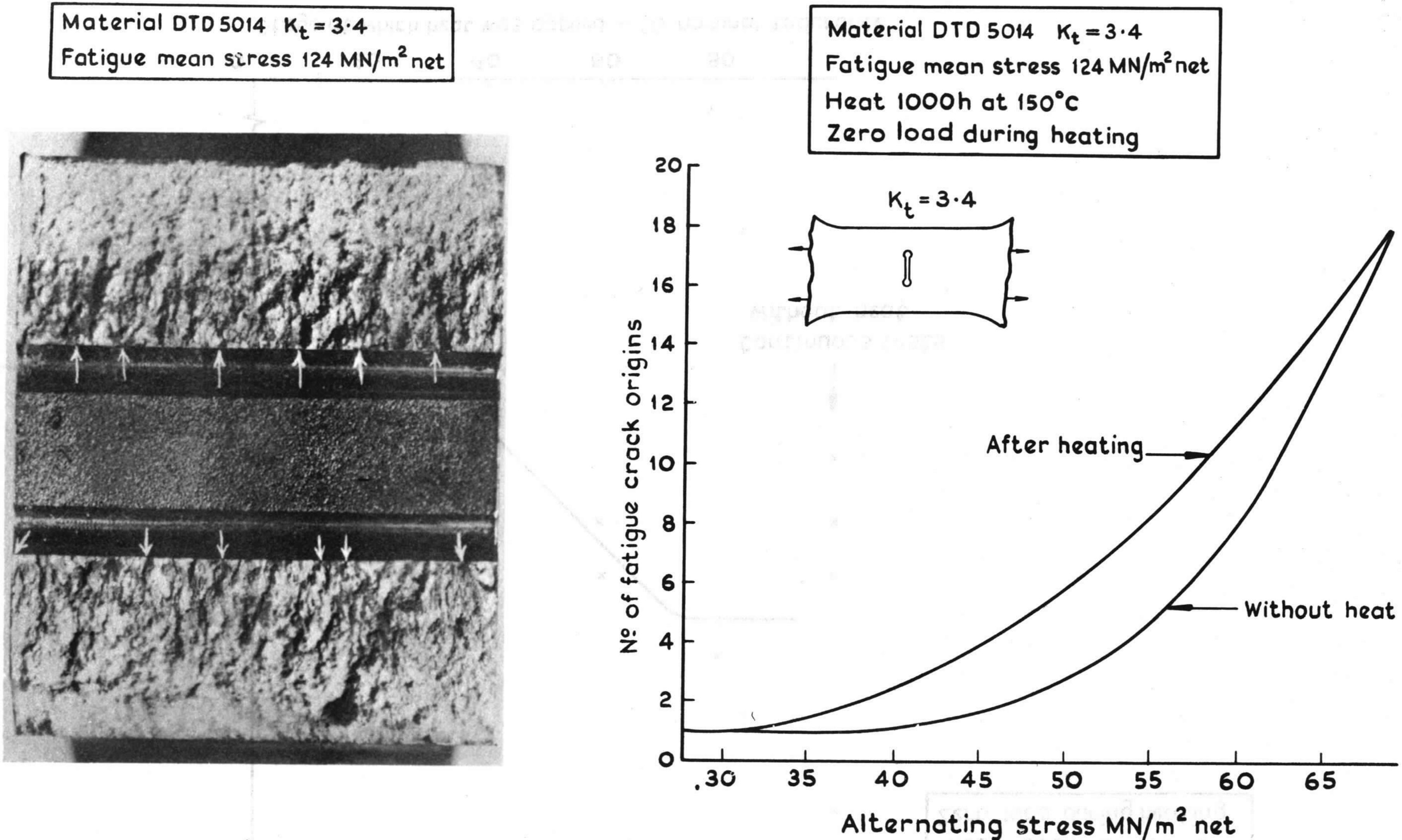


FIG. 2. Effect of applying heat at zero load at some stage of a fatigue test.



(a)

(b)

FIG. 3. Effect of prior heating on the number of fatigue crack origins.

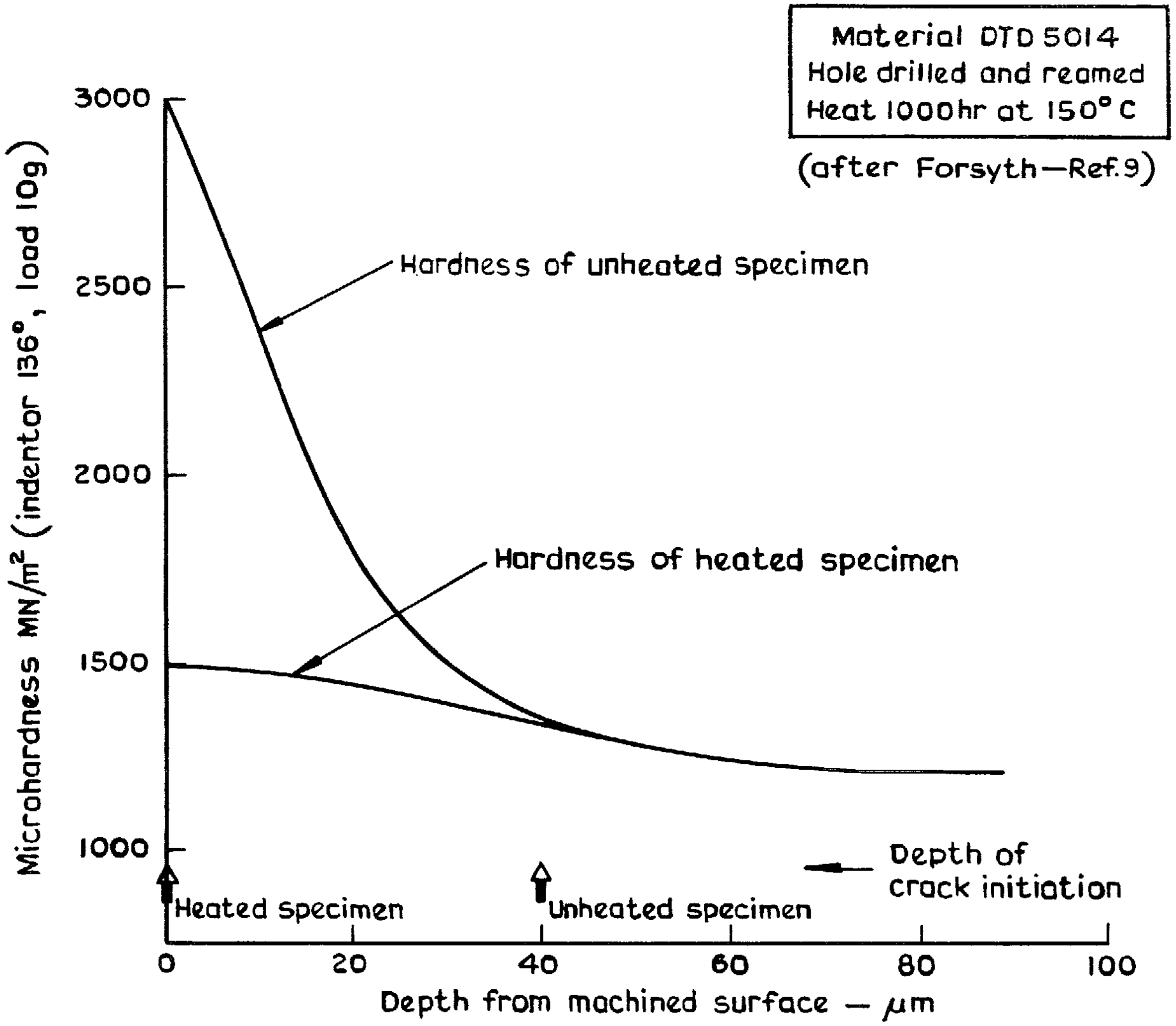


FIG. 4. Effect of heating on surface hardness of a machined hole and depth of fatigue crack initiation.

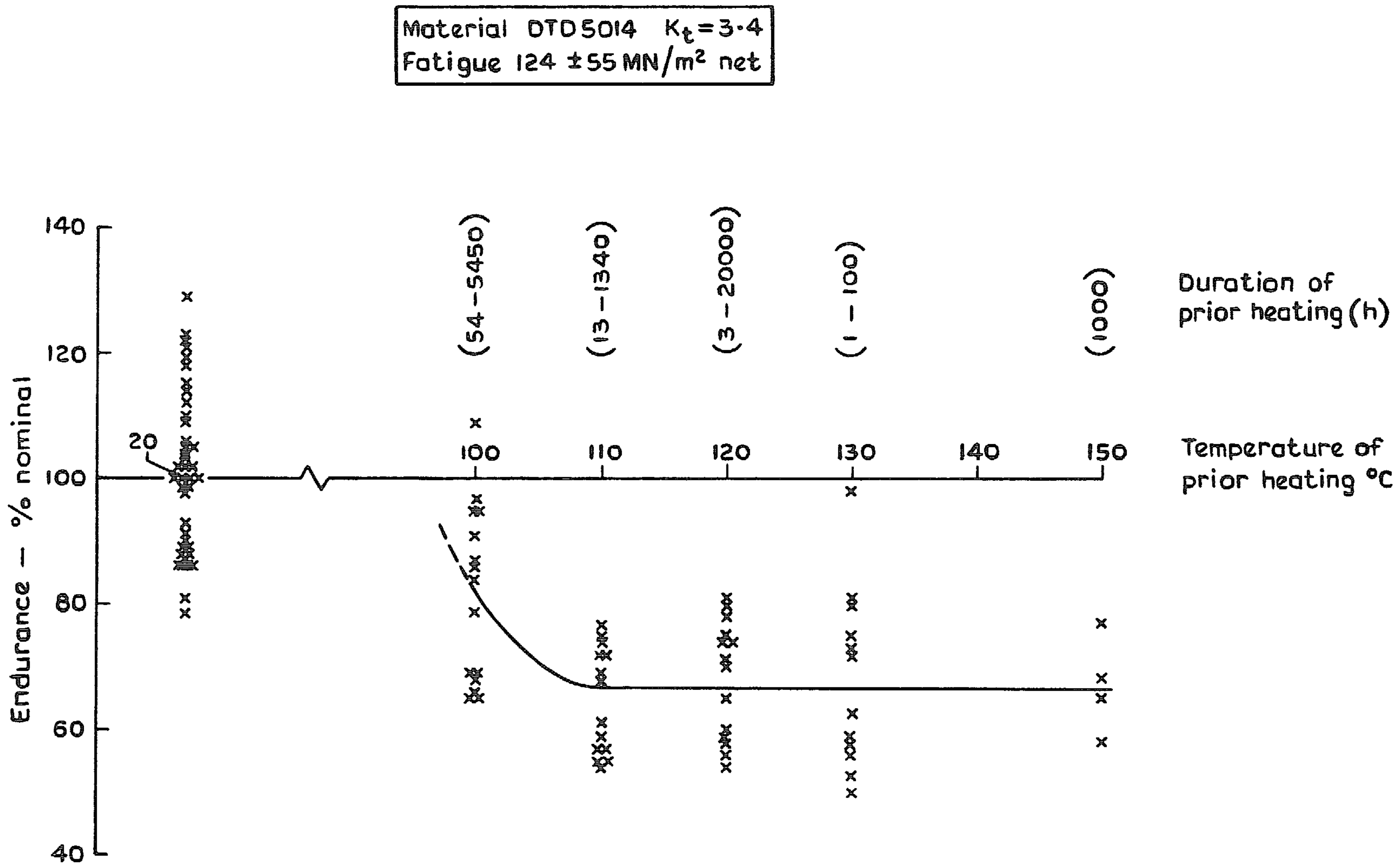


FIG. 5. Effect of prior heating for various times and temperatures.

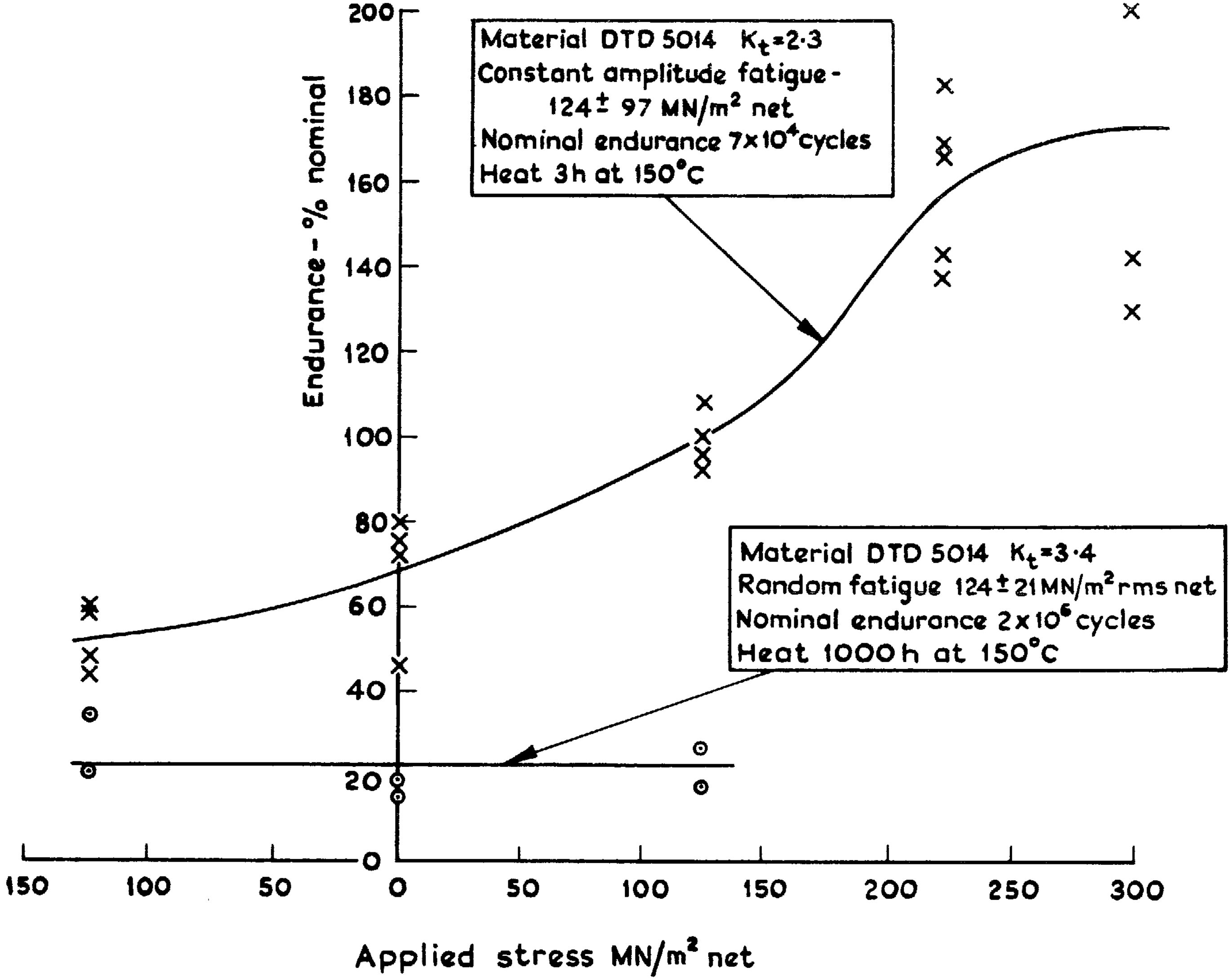


FIG. 6. Effect of applied stress level during prior heating.

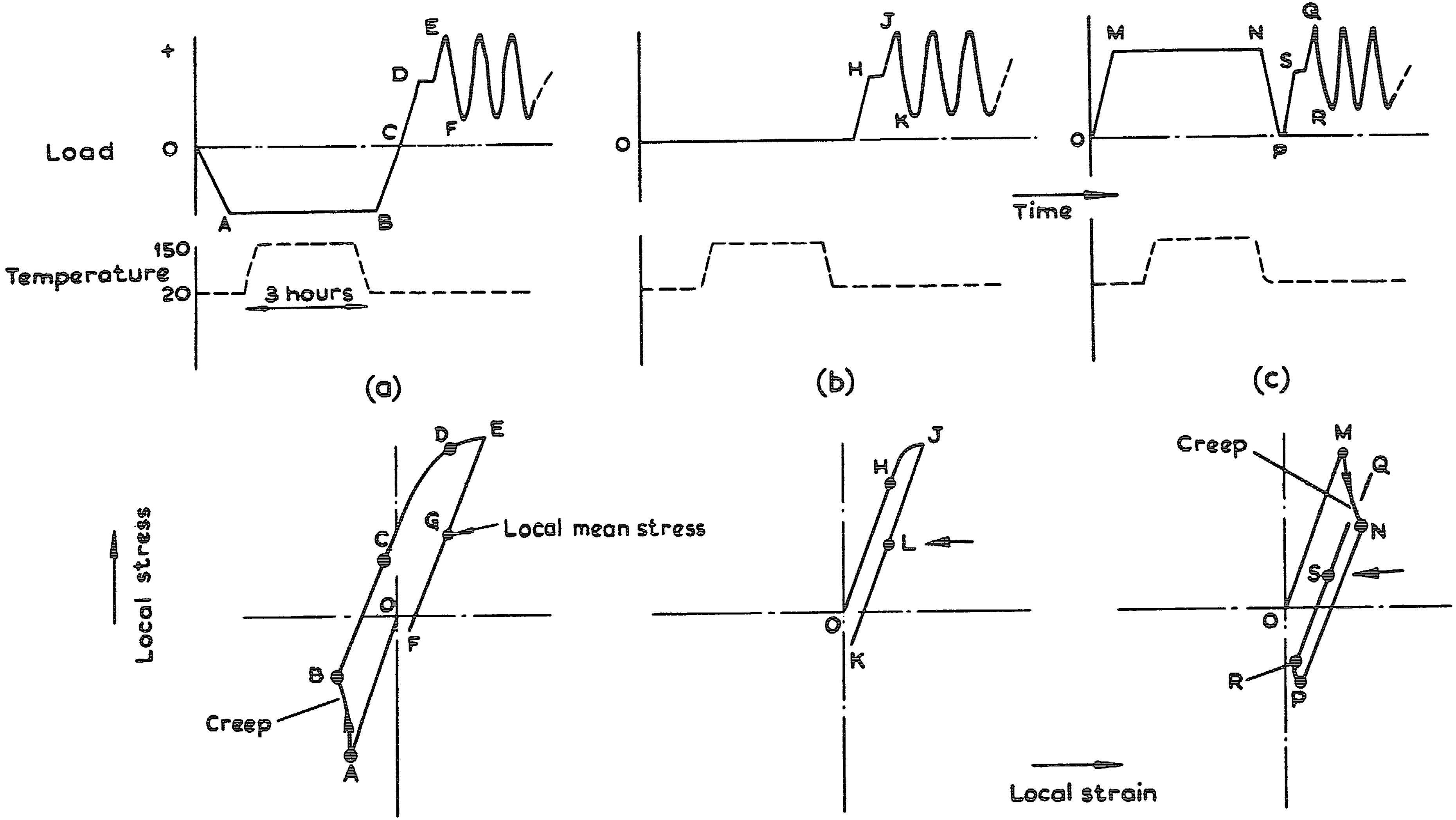


FIG. 7. Effect of creep on local fatigue stress—notch $K_t = 2{\cdot}3$.

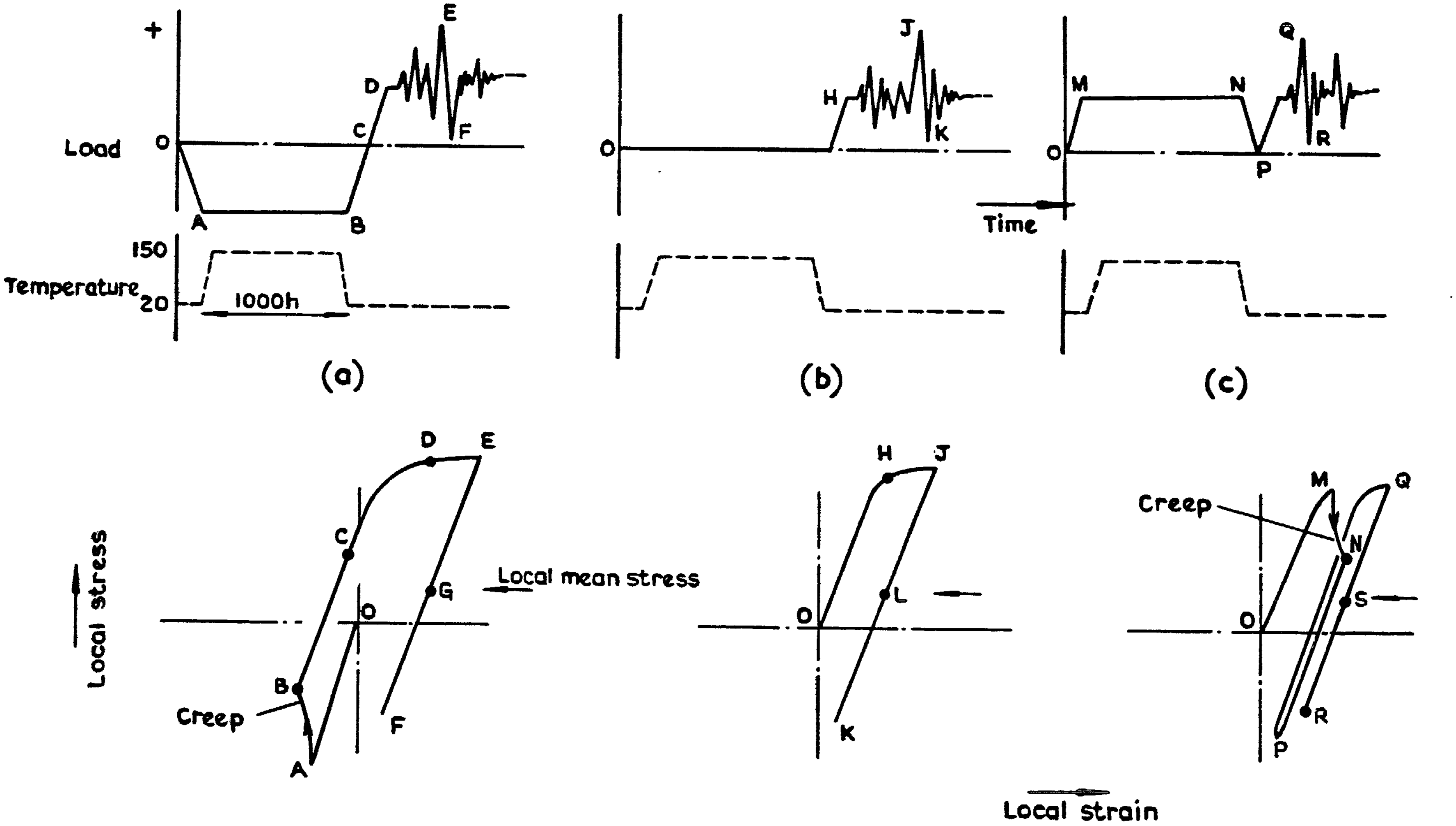


FIG. 8. Effect of creep on local fatigue stress—notch $K_t = 3{\cdot}4$.

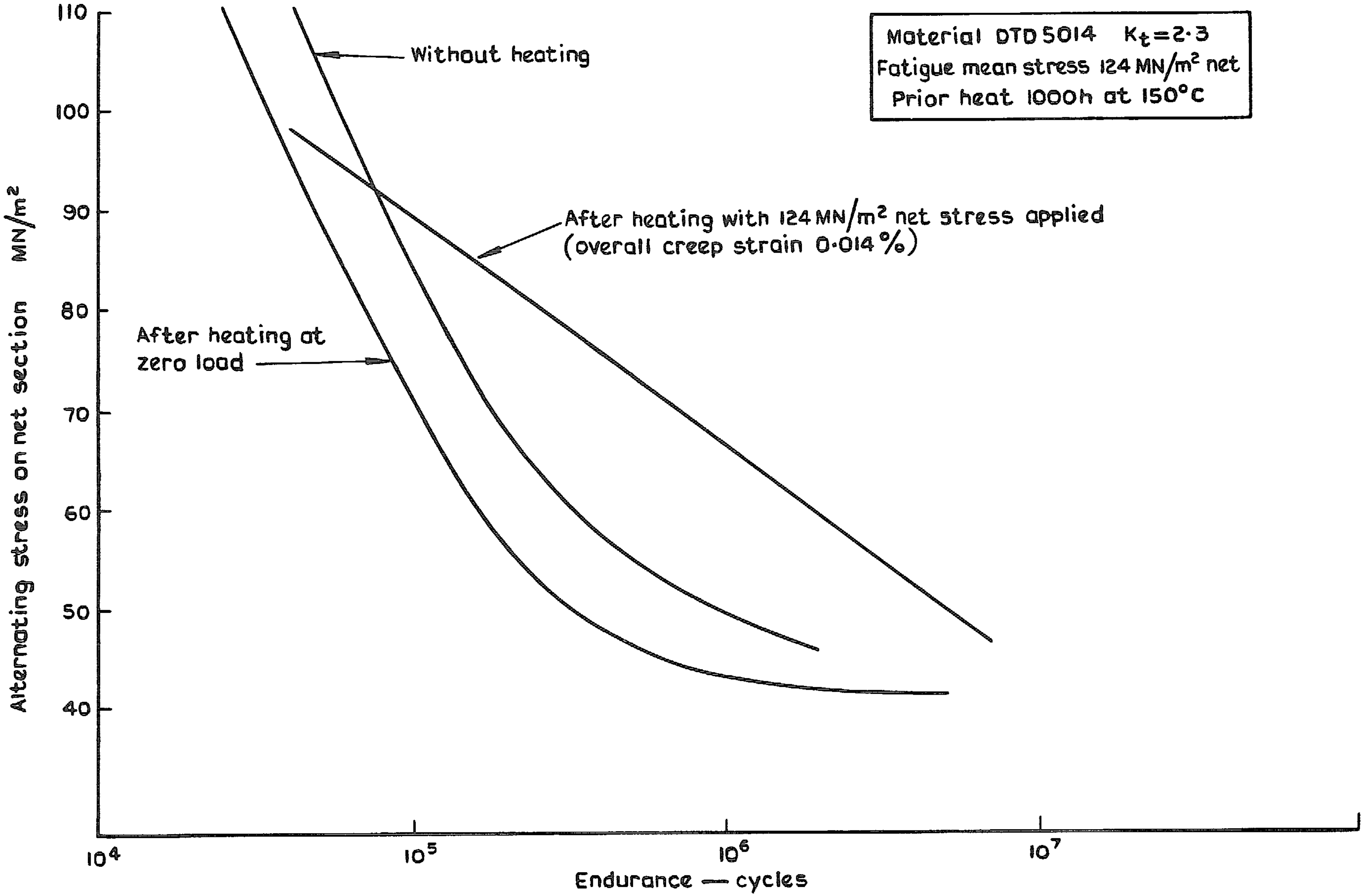


FIG. 9. Effect of heat with and without load on S–N curve.

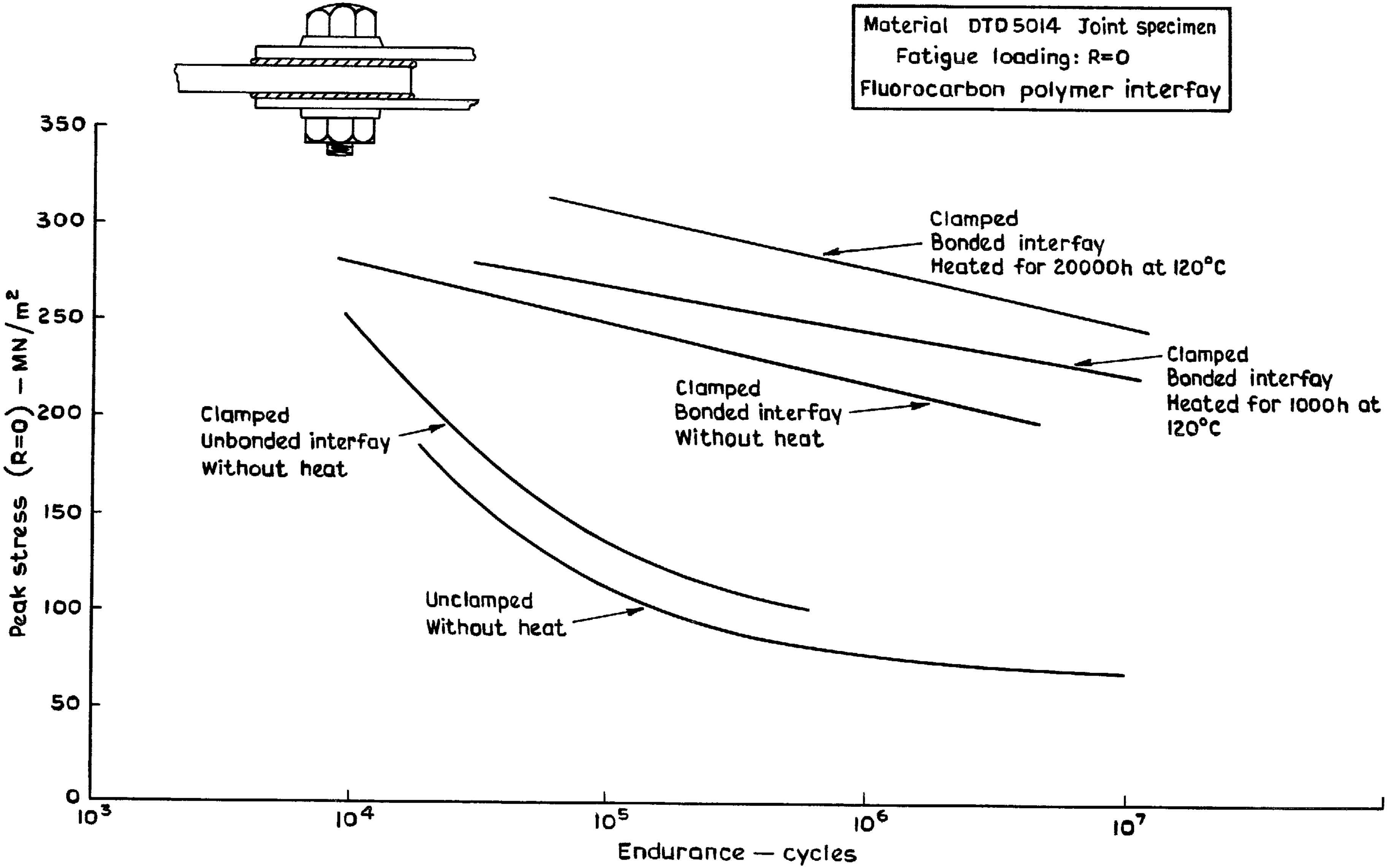


FIG. 10. Effect of heating on clamped joint with bonded interfay.

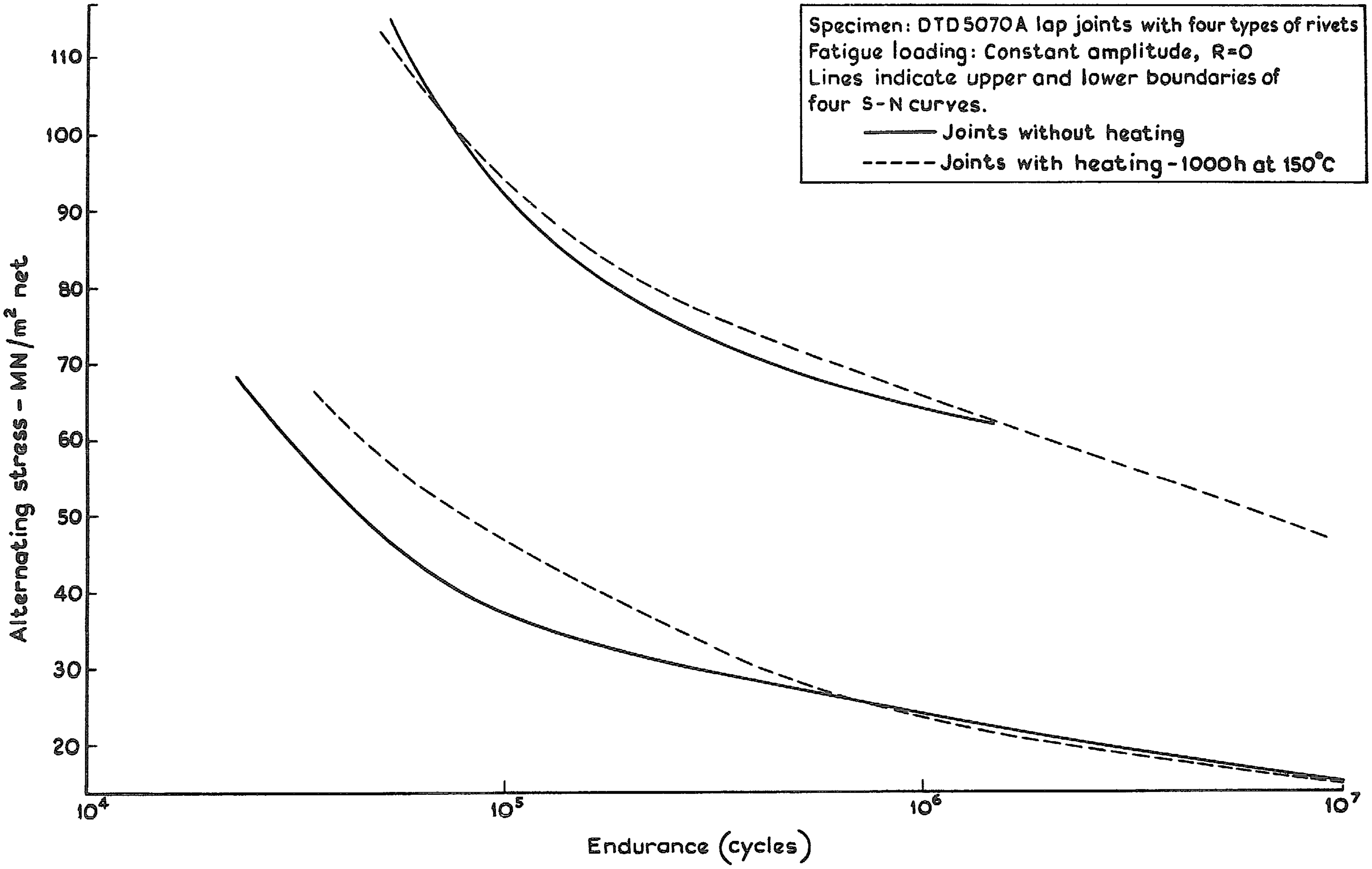


FIG. 11. Effect of prior heat on the range of riveted joint performance.

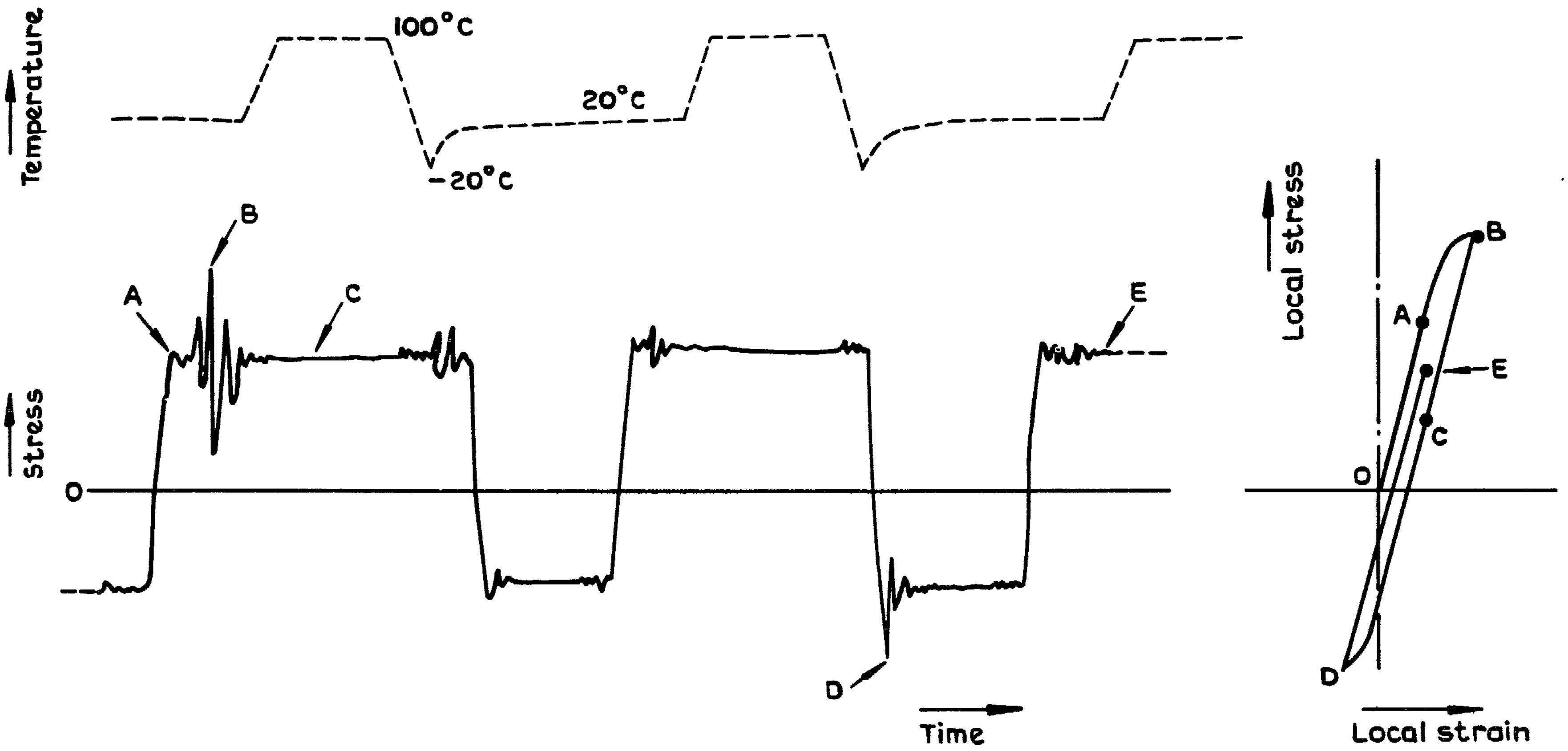


FIG. 12. Stress and temperature sequence on lower surface of wing.

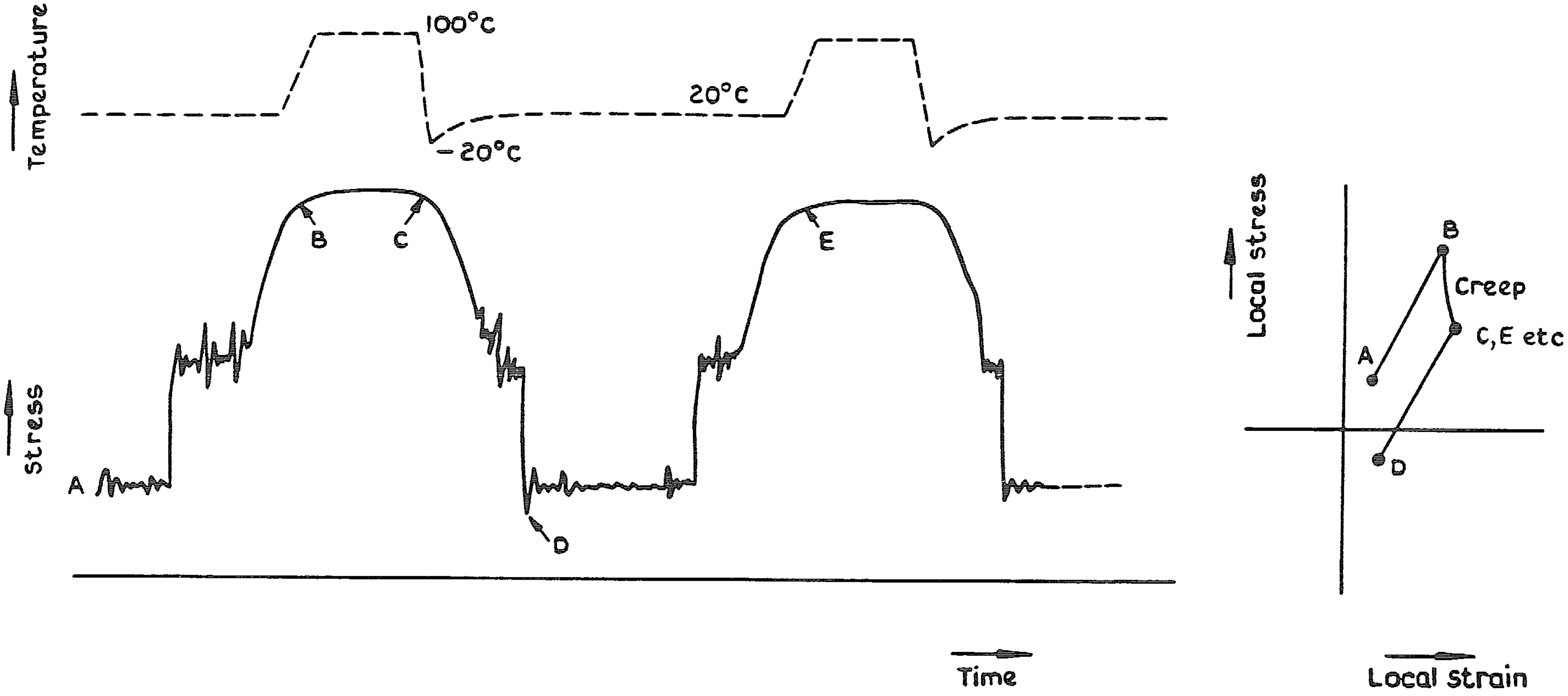


FIG. 13. Stress and temperature sequence on upper surface of fuselage.

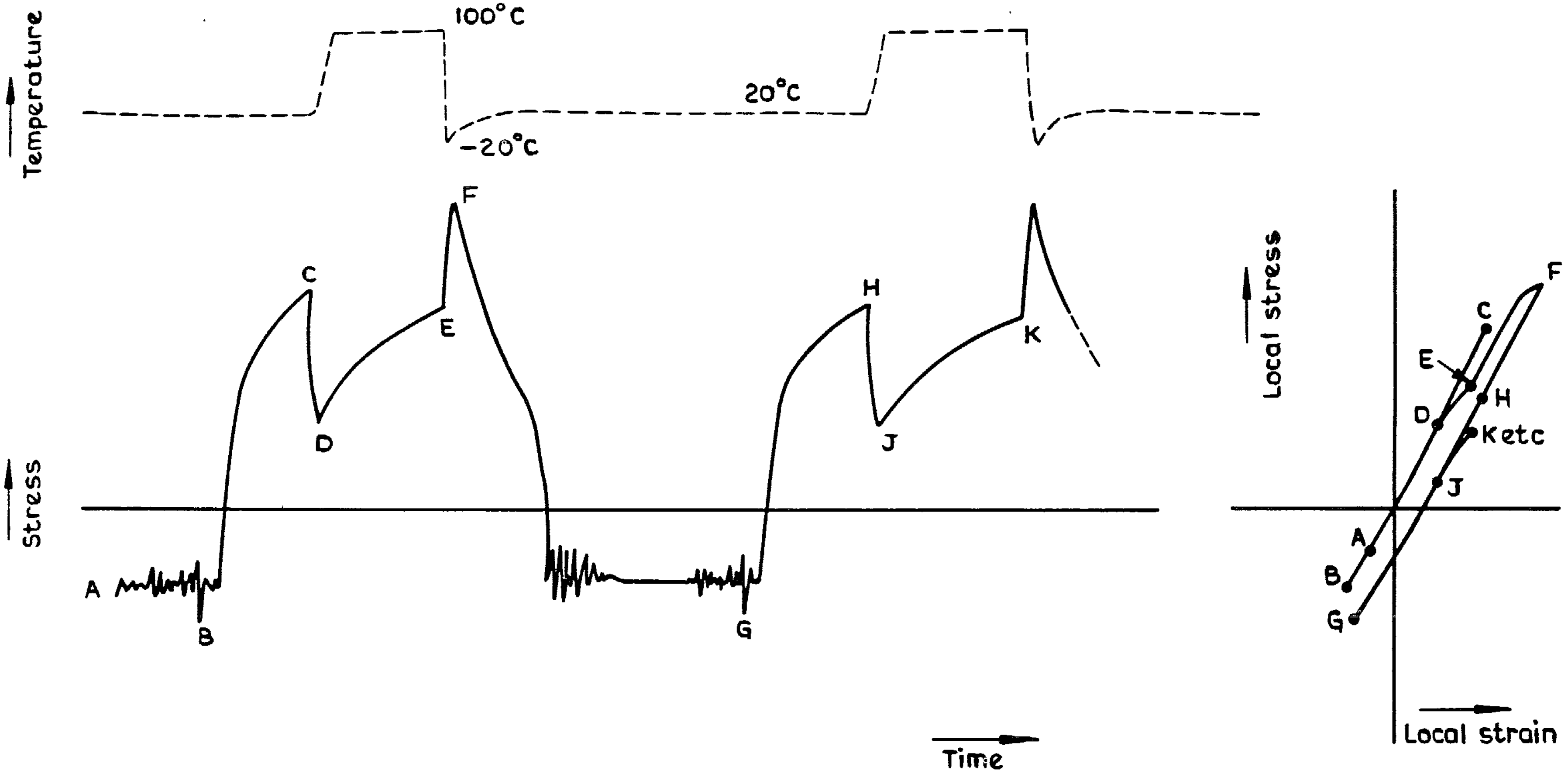


FIG. 14. Stress and temperature sequence on lower surface of fuselage.

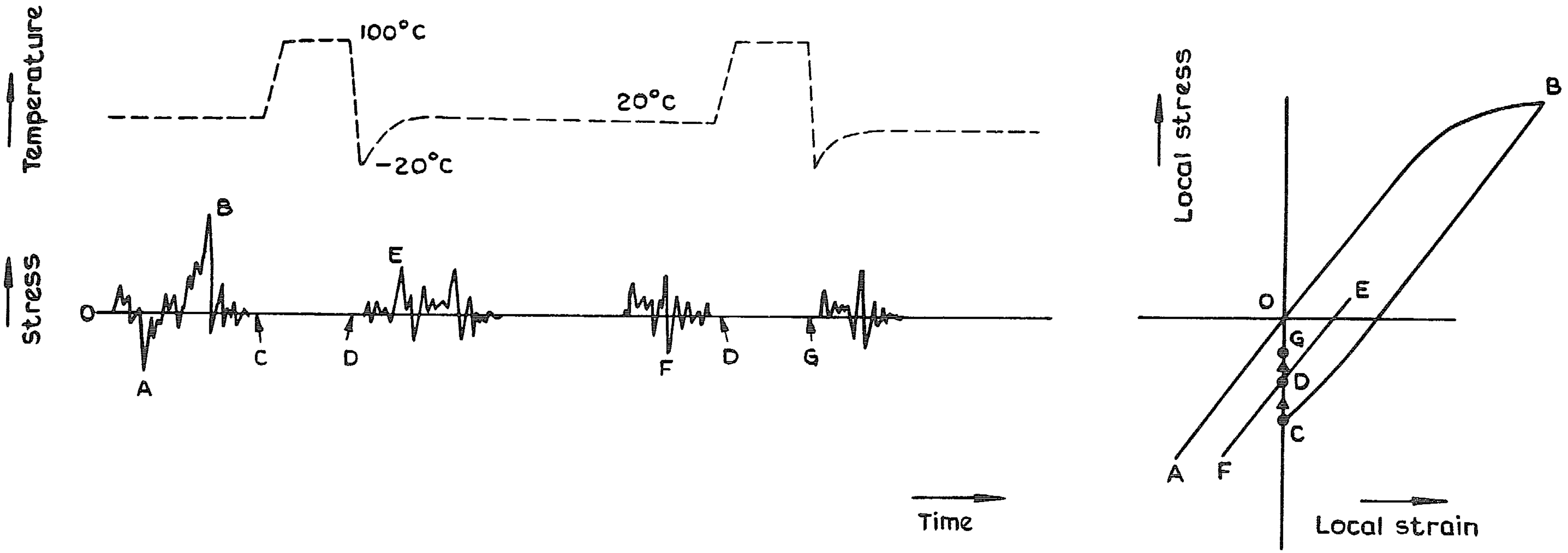


FIG. 15. Stress and temperature sequence at fin root.

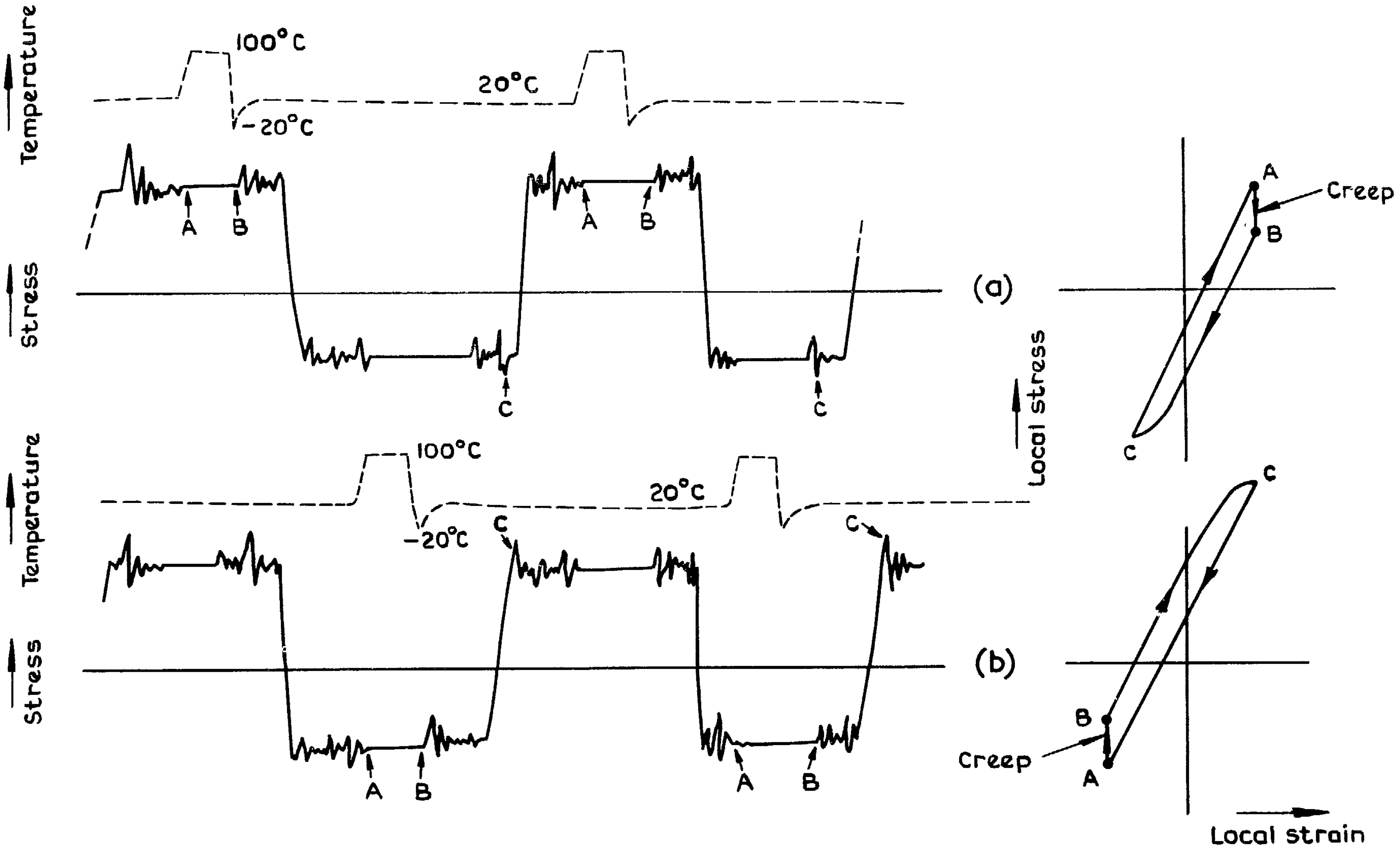


FIG. 16. Examples of plastic cycling induced by creep.

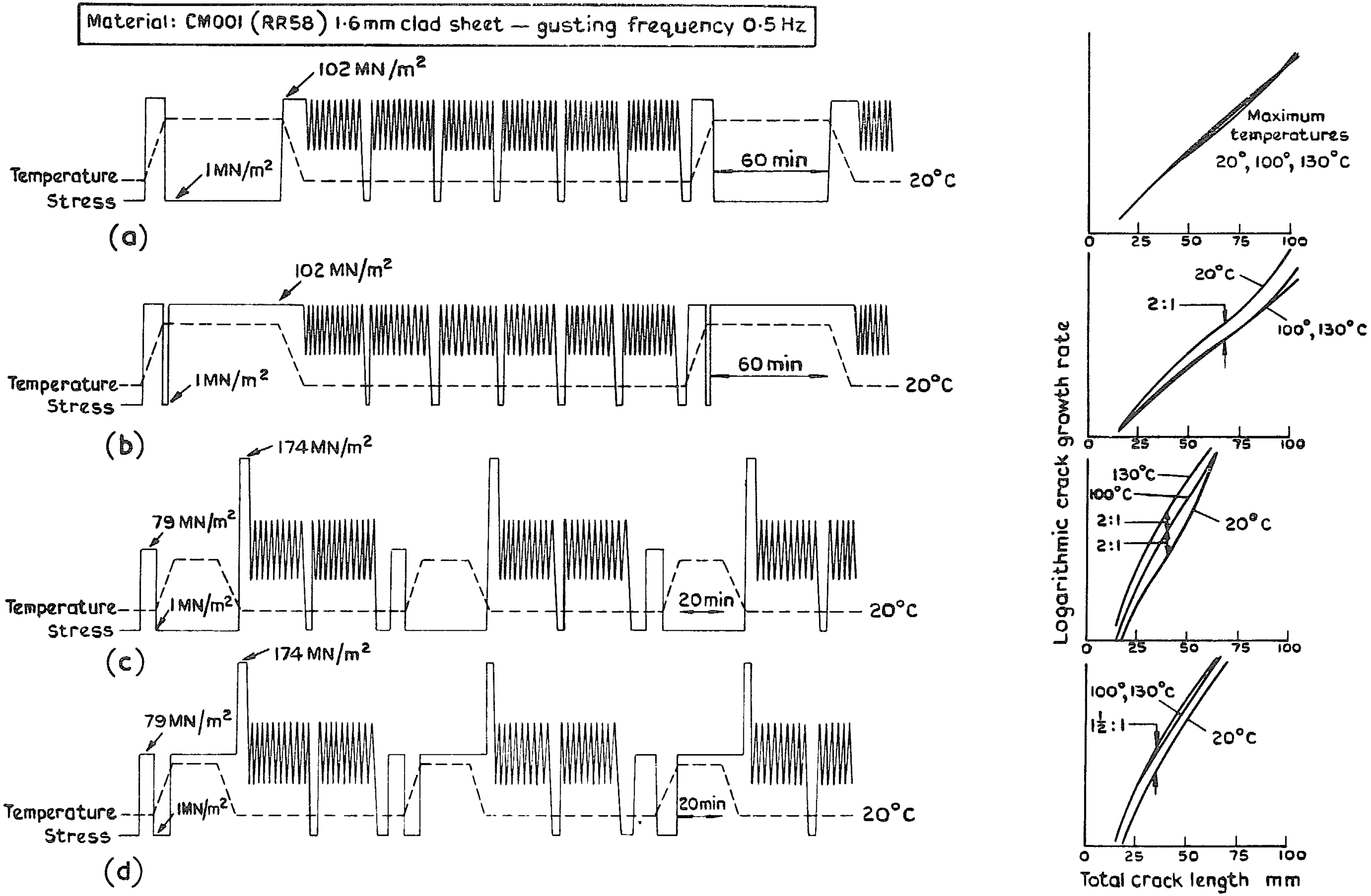


FIG. 17. Effect of intermittent heating on crack propagation.

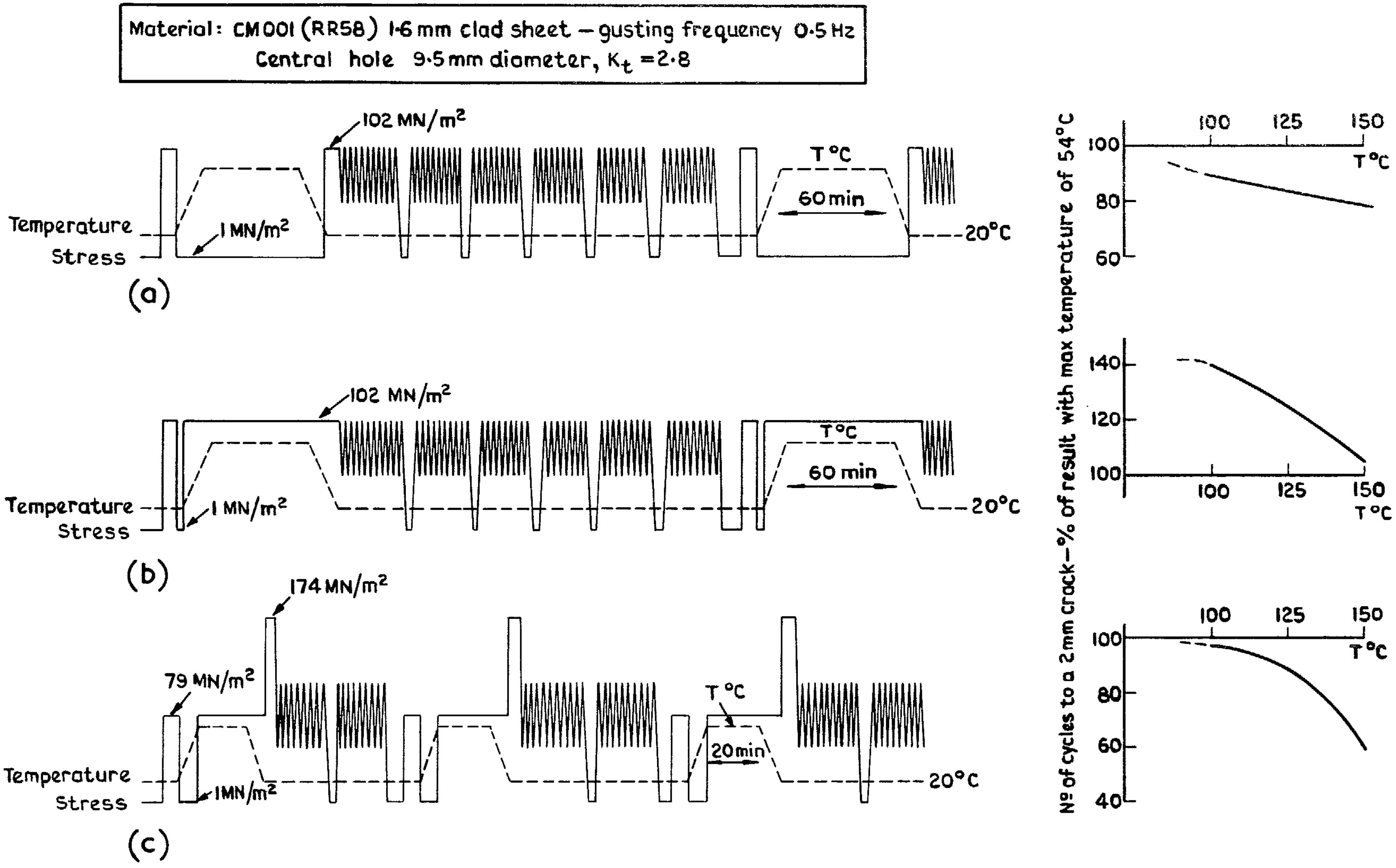


FIG. 18. Effect of intermittent heating on crack initiation and growth to 2 mm.

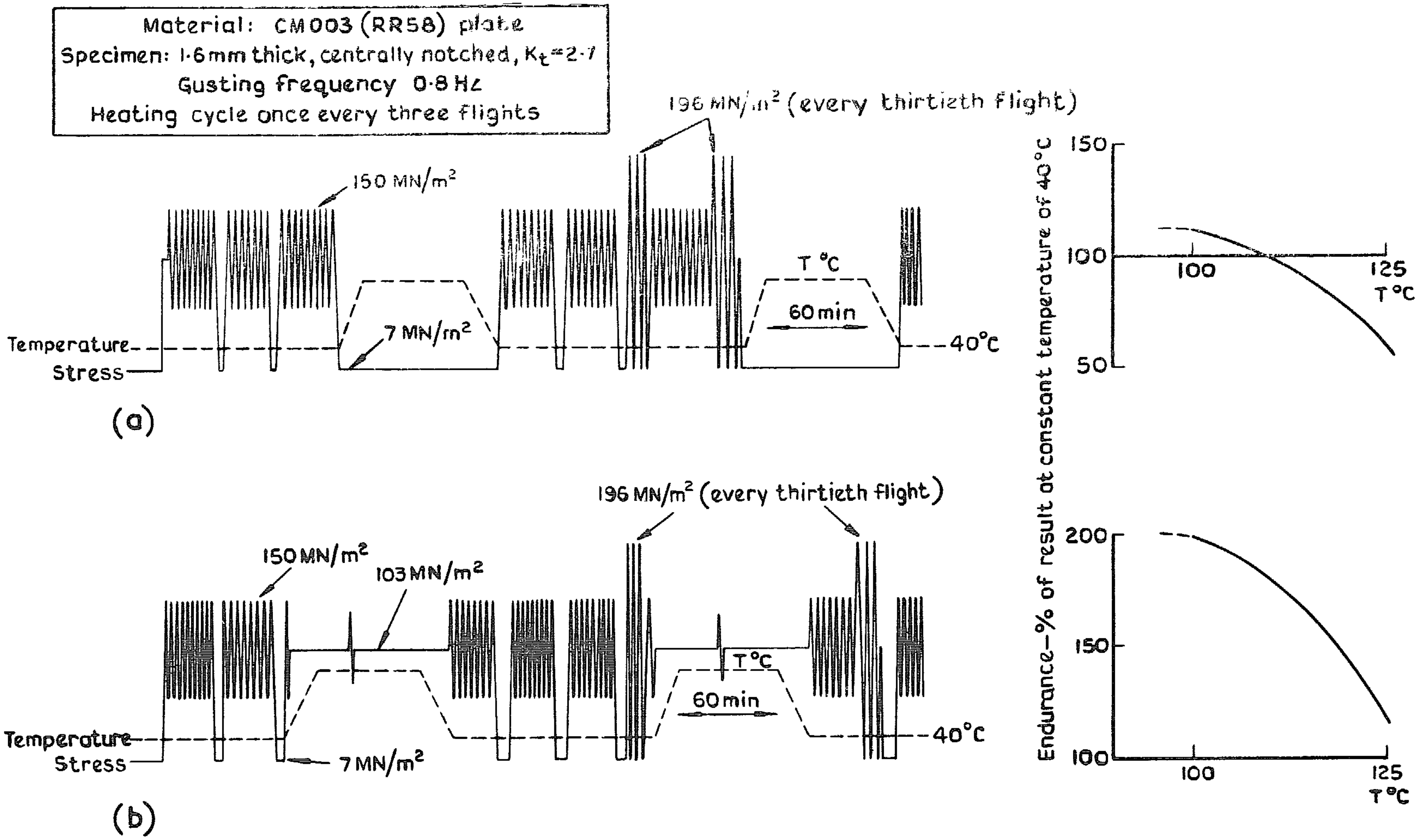


FIG. 19. Effect of intermittent heating on endurance of notched specimen.

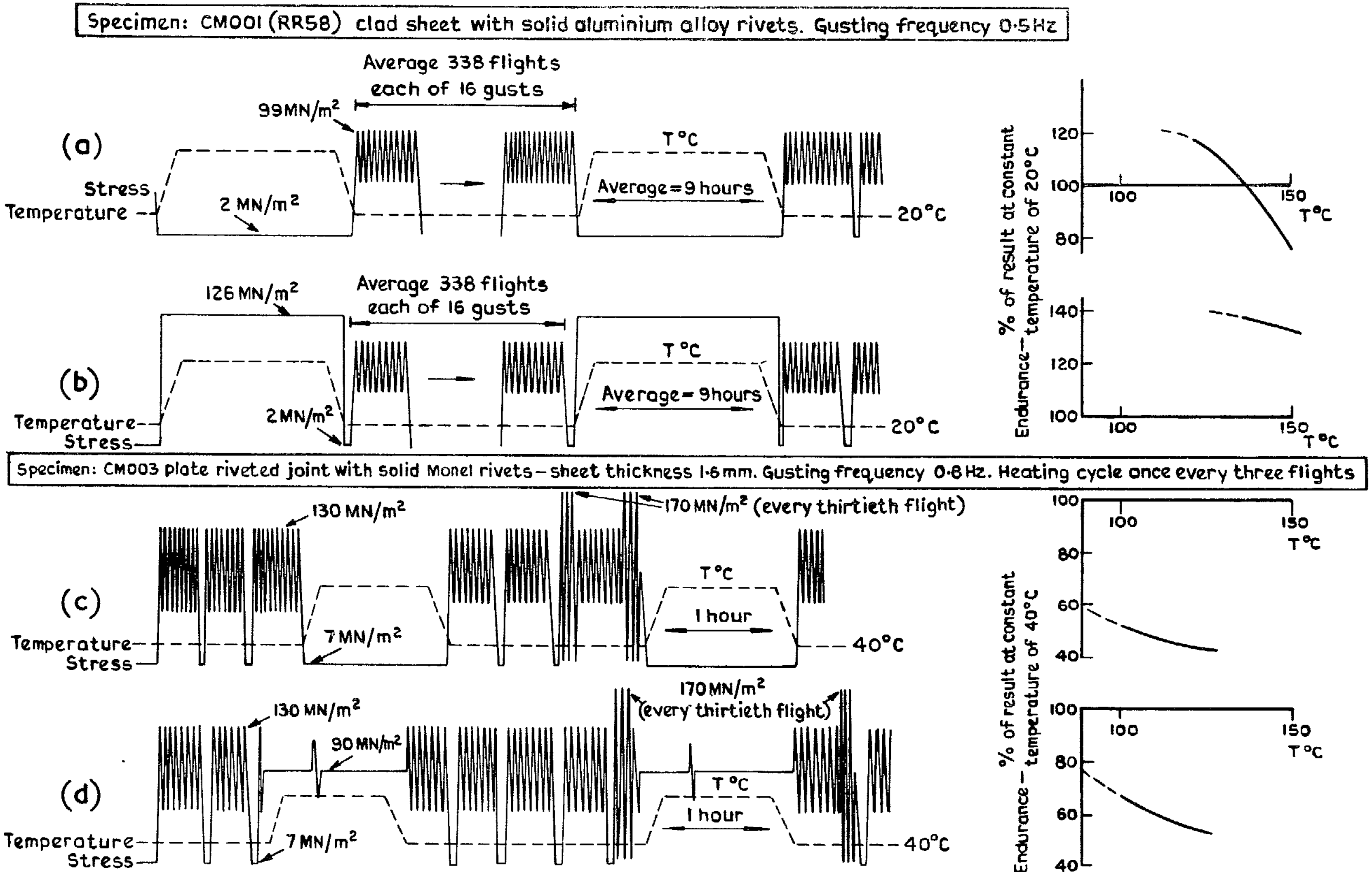
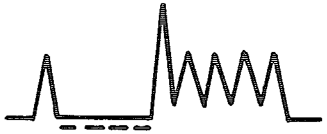
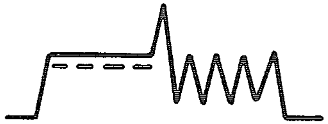
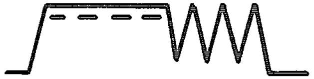


FIG. 20. Effect of intermittent heating on endurance of riveted joints.

		Ratio of life with heating to life without heating				
		Crack propagation	Notch in clad sheet	Notch in machined plate	Riveted joint in clad sheet	Riveted joint in machined plate
A		0·5	⌿	~1·0	⌿	0·5
B		0·7	~1·0	2·0	⌿	0·7
C		~1·0	~1·0	⌿	1·3	⌿
D		2·0	1·4	⌿	1·4	⌿

---- Heating

⌿ Not available

FIG. 21. Effect of intermittent heating at 100°C on endurance of RR58 material.

Printed in England for Her Majesty's Stationery Office by J. W. Arrowsmith Ltd., Bristol BS3 2NT
Dd. 290278 K.5. 7/77.

HER MAJESTY'S STATIONERY OFFICE

Government Bookshops

49 High Holborn, London WC1V 6HB
13a Castle Street, Edinburgh EH2 3AR
41 The Hayes, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
Southey House, Wine Street, Bristol BS1 2BQ
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY

Government publications are also available through booksellers

R. & M. No. 3798
ISBN 0 11 470969 6