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Fatigue life measurement using (BiSb)Te Films

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Accumulated cyclic deformation is considered as a measure of the fatigue life of a construction and (BiSb)Te films have been used to measure it. These gauges can be used for the estimation of both the stress spectrum acting on a material and the remaining service life of a material. The results obtained during the investigations of 2024T3 and 7075T6 alloys show that the kinetics of cyclic deformation accumulation has a definite regularity. The accumulated process consists of four stages, each allowing some judgement to be made concerning the degree of fatigue damage of the material.

1. Introduction

During use of any design under cyclic loads, particularly aircraft facilities, it is very important to know the period of lifetime of the construction, because knowing this the negative consequences of an unexpected fracture can be avoided, and it will then be possible to use a construction for its whole lifetime.

Many results on metals fatigue research confirm the well-known fact that some plastic microdeformation always preceeds fatigue failure. Plastic microdeformation accumulates during any prolonged period of cycling below the macroscopic yield stress of the material [1]. It is usually termed the accumulated cyclic deformation, ε_{acc}, and is caused by multiplication and rearrangement of dislocations under cycling. The process of cyclic deformation accumulation in the material does not obey the law of linear summation of small deformations [1] and takes place not only along the direction of load action, but along any direction. These circumstances and also the small value of accumulated cyclic deformation cause great difficulty in its measurement by methods using the usual strain gauges. Even if accumulated cyclic deformation could be measured sufficiently accurately, there still remains the unclear question, in what way is it possible to predict the service life of the material by the accumulated cyclic deformation value?

A simple and accurate method of accumulated cyclic deformation measurement using (BiSb)Te thin films is suggested here. Using this method we have managed to determine that the process of cyclic deformation accumulation in the material proceeds according to a quite definite law which allows prediction of the service life of this material at any time with the accuracy determined by the spread of the number of cycles.

2. Experimental procedure

Semiconductor (BiSb)Te films produced by thermal spraying on any base or a specimen have not been sufficiently investigated as fatigue gauges and thus require systematic study. For example, one would like to know what causes increase of the electric resistance of a film during fatigue tests – it could be either due to structure changes within the film itself or as a result of the accumulated cyclic deformation in the specimen. For this purpose an X-ray diffraction (XRD) study of the (BiSb)Te film structure has been carried out for films deposited on both polyimide bases and on aluminium alloy specimens.

In the first case the XRD patterns illustrate some excesses over the background wherein more intensive bismuth lines must be observed. Naturally, it is impossible to consider them unquestionably as crystal phase reflections because of their very small intensity and spreading. A comparison with the control XRD patterns of the polyimide bases allows the conclusion to be drawn that the structure of the (BiSb)Te films is roentgenoamorphous.

In the second case, in all the XRD patterns obtained from the (BiSb)Te films, additional clear reflections of small intensity have been fixed. The position corresponded to the strongest (1 0 2) Bi lines. Unfortunately, short (0 1 4) and (1 1 0) Bi lines were almost coincident with the (1 1 1) Al lines. The others were found at the background level because of their weak intensity. The latter hampers the interpretation of the XRD patterns. However, it is sufficiently definite that the (BiSb)Te films deposited on the crystal aluminium alloy contain some crystalline component which represents a lattice of tellurium and antimony solid solution in bismuth solvent. The small intensity and spreading of the reflections signifies a small quantity of the phase and its crystal imperfection.

Thus, the (BiSb)Te films deposited on the non-crystal line surface may be considered as roentgeno-amorphous but those on a crystal line contain small "islands" of a crystalline phase. After 300 000 cycles of specimens at $\sigma_{max} = 170$ MPa, changes in the XRD

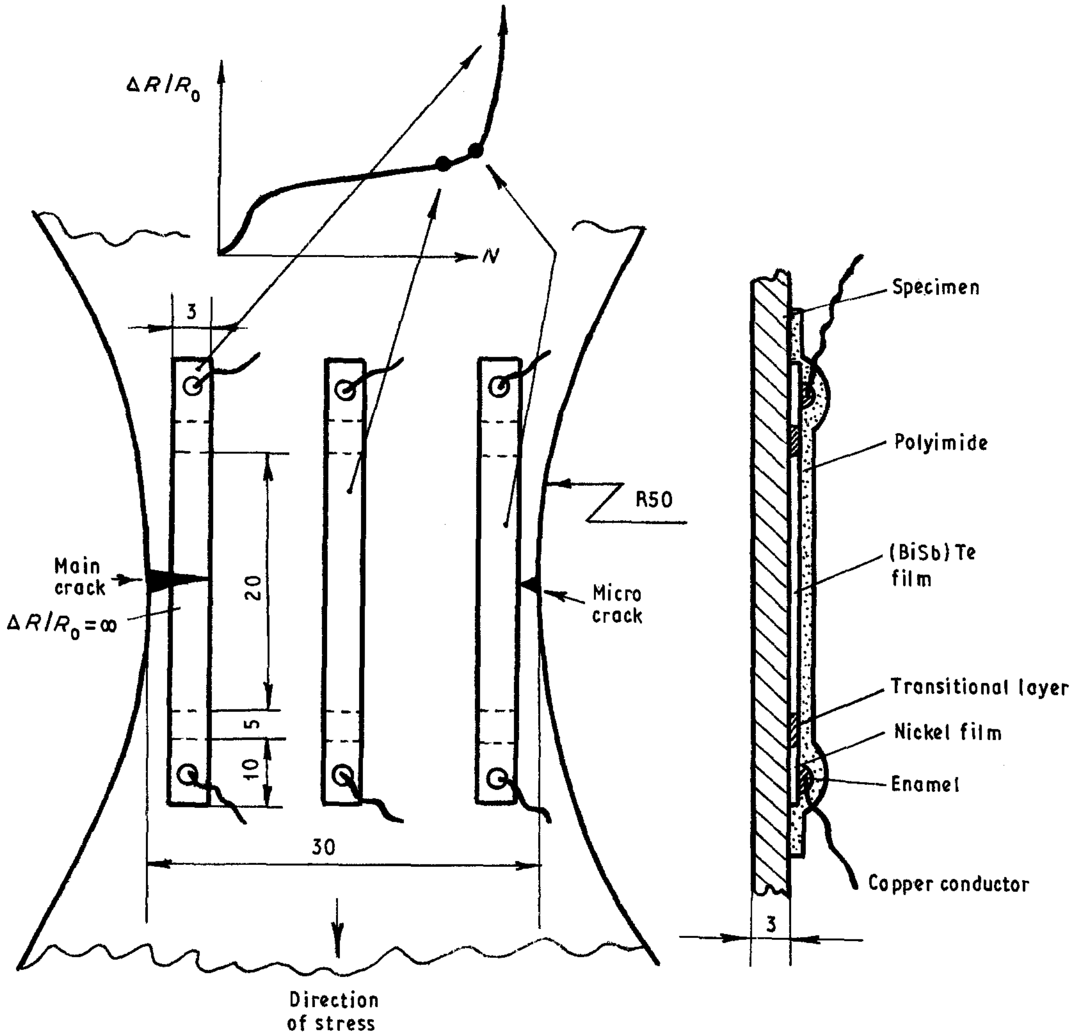

Figure 1 Shape and dimensions of the specimens and the (BiSb)Te films.

patterns of the films were not observed in either case. Thus the degree of crystallinity of (BiSb)Te films during cycling was not increased. It can be assumed that the accumulation of deformation changes in the (BiSb)Te film structure is negligible during the whole cycle operation time of the specimens, so the (BiSb)Te films have a clear tensity resistive effect.

The second question regarding technique to be cleared up is the determination of the $\Delta R/R_0$ dependence of the (BiSb)Te films on the deformation of the specimens. For this purpose, (BiSb)Te films were deposited on one side of the specimen. On the other side, the same films, deposited on a polyimide base, were glued on.

Specimens without concentrators are shown in Fig. 1. The arrangement of films on them may be of any kind: along, across or with some degrees to the direction of the loading action. The specimens with circle concentrators in the centre were also used. Specimens were tensile tested in the elastic region and the $\Delta R/R_0$ of the (BiSb)Te films were measured with the load. Assuming Hooke's law to be obeyed, the stresses were converted in strains. The $\Delta R/R_0$ dependences of (BiSb)Te films on the deformation of the specimens were the same for the glued and deposited films and are presented in Fig. 2 as a united curve. The $\Delta R/R_0 = f(\varepsilon)$ dependence consists of two parts which can be approximated by straight lines. Below the 2×10^{-3} deformation level, the electric resistance increase during specimen deformation was small (the gauge factor of the strain gauge is about 200). At higher strains this increase was greater (about 800).

Naturally, such a form of the $\Delta R/R_0 = f(\varepsilon)$ dependence causes some difficulties in conversion of $\Delta R/R_0$ into accumulated cyclic deformation ε_{acc}. However, this is not so important for practical purposes when it is necessary to know the moment of exhaustion of cyclic deformation accumulation. Such a high level of gauge factors of the strain gauge can be explained by the peculiarities of the structure of (BiSb)Te film, its structure being layer-chained. In this case, fluctuating energy levels can arise quite easily inside a forbidden zone. The concentration of these levels can be up to $10^{19}\,cm^{-3}$. If the Fermi level is higher than the fluctuation levels the deformation of the films induces strong changes in its resistivity.

The maximum deformation of the specimen which the (BiSb)Te film can measure without its own failure occurring is $\sim 5 \times 10^{-2}$–1×10^{-1}. This is the same for the film no matter what type of specimen deformation occurs, static, dynamic or fluctuating deformation, in any case the film fixes complete deformation of the specimen at any time. When loading is relieved completely the film shows residual deformation of the specimen only. If the latter is equal to zero (usual in the case after a single small loading only) the electrical

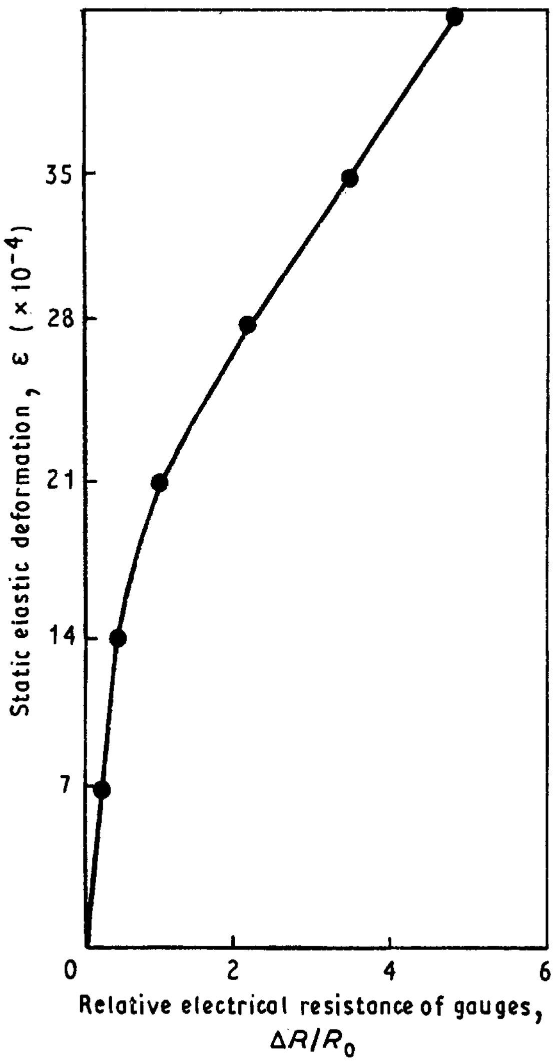

Figure 2 Variation of the relative elastic static deformation, ε, of the specimen with $\Delta R/R_0$ of the (BiSb)Te film cemented on it.

resistivity of the film remains equal to the original one. Therefore, (BiSb)Te films are suitable for measuring elastic and a small plastic deformation only, i.e. they are particularly suitable for accumulated cyclic deformation.

Problems exist in mounting the gauge on the specimen. It is best to deposit the (BiSb)Te film directly onto the object studied. However, the deposition of films on a particular construction is difficult to realize in most cases, so the technique of film deposition on a base (which is then cemented on the constructive element) has been preferred. Our investigations into mounting the (BiSb)Te films deposited on a base revealed polyimide and lavsan to be the most suitable bases.

The form and sizes of films may be different for various cases but their thickness must be ~ 2 μm. The films deposited on the polyimide and lavsan bases were glued on to the specimens by the front side along the full length of the films. This excluded the possibility of misrepresentation of any indication which appeared due to the relaxation processes in the base and simultaneously protected the thin films from external effects. The leads supplying current to the films were deposited simultaneously with the film. They were nickel and about 10 mm in length. Copper conductors were glued on to nickel regions of the films by a current-conducting enamel. The primary electrical resistance of the films was about 30–300 Ω, the length being 10–20 mm, the width 3 mm. Between three and six films were cemented on to each side of the specimen along the direction of the loading action. An ordinary digital voltmeter was used to measure the electrical resistance. An amplifier apparatus for the tensity resistive effect is not required.

Accumulated cyclic deformation determined by the (BiSb)Te films was investigated on specimens of aluminium 2024T3 and 7075T6 alloys. The specimens were anodized. The surface oxide film was about 5 μm thick and allowed the (BiSb)Te films to be cemented by the front side. Fatigue tests were carried out using a pulsating stress cycle, the frequency being 8 and 0.2 Hz. The cycling ratio was 0.05. The electrical resistance of the films was measured in the unloaded condition immediately after every halting of the fatigue tests and also ~ 10 min after this. The moments at which tests were stopped were chosen when some changes were expected in the fatigue life of the stressed specimen, or when checks of $\Delta R/R_0$ were required. The time of every measurement was ~ 5 s.

In this paper the $\Delta R/R_0 = f(N)$ curves are presented as the dependence on the number of cycles but not upon log N. Such a representation is caused because the region at $N < 10^3$ cycles is of no practical interest and the probability of fatigue failure in it is sufficiently small. The more interesting period of fatigue tests was at $N > 10^4$ cycles when the specimen fatigue failure occurred.

3. Results and discussion

Fig. 3 shows the $\Delta R/R_0 = f(N)$ dependences for the three (BiSb)Te films cemented on one of the sides of the 2024T3 alloy specimen. The first and third films were cemented to the edges of the specimen, and the second to the centre (Fig. 1).

Four typical regions were observed on the $\Delta R/R_0 = f(N)$ curves. The first corresponding to 3% durability has only a small $\Delta R/R_0 = f(N)$ increase, that is obviously caused by the small value of the accumulated cyclic deformation at the beginning of cycling. The second region accounts for 10%–15% durability and corresponds to the intensive growth of $\Delta R/R_0$ during cycling. The third region of the $\Delta R/R_0 = f(N)$ curve has a gentler slope and illustrates essentially smaller $\Delta R/R_0$ growth. This is the longest period of the tests. The fourth region accounts for about 4% durability and is characterized by the rapid increase of $\Delta R/R_0$. It was presumably caused by the macroscopic deformation connected with microcracks merging into the main fatigue crack and it was observed near the crack (Fig. 1).

In order to determine which portion of $\Delta R/R_0$ of the films is caused by the cyclic damage in the specimen, and which is the portion of the cyclic damage in the films themselves, fresh (BiSb)Te films were glued on the specimen after 2×10^5 cycles at $\sigma_{max} = 170$ MPa. The fatigue tests were continued until the specimen failed. The $\Delta R/R_0 = f(N)$ dependences for the films which were glued on the specimen before

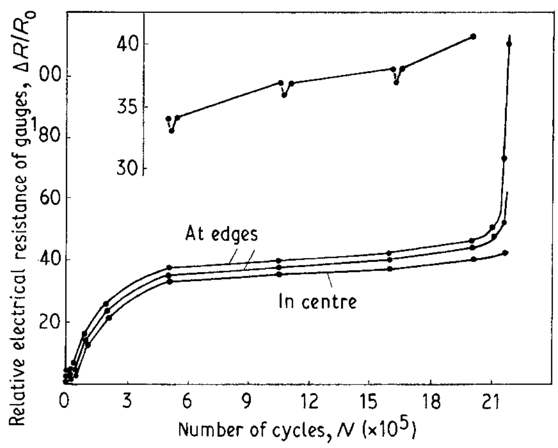

Figure 3 Variation of $\Delta R/R_0$ of the films cemented on the edges and in the centre of the specimen with the number of cycles of the 2024T3 specimen at σ_{max} = 200 MPa. The inset gives details.

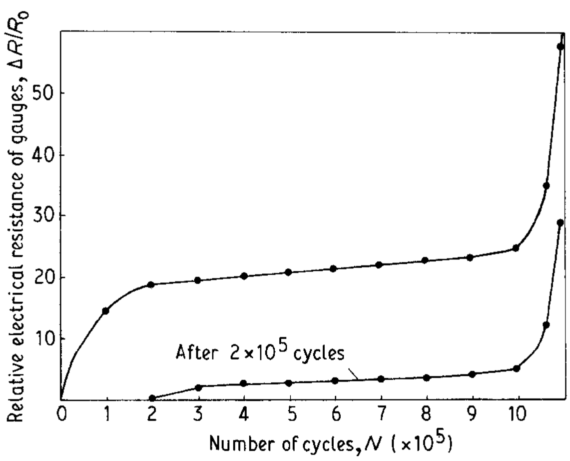

Figure 4 Variation of $\Delta R/R_0$ of the films glued to the specimen before cycling and after 2×10^5 cycles with the number of cycles of the 2024T3 specimen at σ_{max} = 170 MPa.

the tests (gauge 1) and after 2×10^5 cycles (gauge 2) are arranged in equidistant fashion and are presented in Fig. 4. Gauge 2 shows no primary ascent of the $\Delta R/R_0 = f(N)$ curve. Thus, the ascent is caused by cyclic damage in the specimen but not in the film, otherwise a primary ascent of $\Delta R/R_0 = f(N)$ would be observed in both films cemented at the beginning of cycling and after 2×10^5 cycles. It may be illustrated that after glueing the films to the specimen after a different number of cycles, all the $\Delta R/R_0 = f(N)$ dependences look like those of gauge 1.

These results and the data of the XRD analysis concerning the amorphous structure of the films reveal the change in the electrical resistance of the films to be proportional to the change in the accumulated cyclic deformation of the specimens. They also provide evidence that under fatigue tests the cyclic damage accumulation in the amorphous structure of the films may be neglected in the first approximation, and the change of $\Delta R/R_0$ curve in Figs 3 and 4 is caused by the cyclic plastic deformation accumulation in the specimen.

Unfortunately, it is doubtful whether $\Delta R/R_0$ can be converted into accumulated cyclic deformation using the plot in Fig. 2. However, this is not necessary in practice because $\Delta R/R_0 = f(N)$ curves provide sufficient information about different stages of the fatigue process.

Fig. 3 shows the so-called "edge effect" consisting in the concentration of accumulated cyclic deformation closer to the edges of the specimen without concentrators in the centre. In the centre of the specimen the accumulated deformation is somewhat smaller. Such a distribution of cyclic deformation is already visible at the second stage of accumulation (Fig. 3), that is, at the very beginning of cycling. Therefore, cyclic deformation is more accumulated in those sections of the specimens where a fatigue crack will be initiated. Fig. 1 illustrates this situation.

Fig. 3 (inset) shows the $\Delta R/R_0$ value to differ when the measurements are carried out immediately after stopping the test and after $\geqslant 10$ min delay. It can be seen that $\Delta R/R_0$ is slightly decreased. However, after repeated cycling of about 500 cycles its value recovers to that which had been achieved before.

This behaviour of the specimens can be explained by dislocation relaxation processes which result in considerable nonelastic deformations especially if a relaxing element is not a unit dislocation, but a flat dislocation pile up. An abnormal relaxation aftereffect appeared in aluminium, copper, nickel etc., but an especially large aftereffect appeared in dispersion-hardened alloys deformed in a metastable state.

To avoid some measurement distortions, it is necessary to accept any single method of measurement: either to measure resistivity immediately after stopping the test or after $\geqslant 10$ min delay. If this effect is not taken into account, the error can reach about 3%. Apparently it is the result of relaxation processes of dislocation structures in the specimen. It should be noted that the rest period of more than 10 min after the cessation of stressing has no influence on the value of cyclic accumulated deformation at all.

Fig. 5 illustrates the $\Delta R/R_0 = f(N)$ dependences for different maximum stresses of the cycle, σ_{max}. The character of these dependences for all σ_{max} is seen to be the same, the $\Delta R/R_0$ level being quite different. The higher σ_{max}, the larger is the level of $\Delta R/R_0$ and, therefore, the larger the value of the accumulated cyclic deformation before failure, the shorter is the third gently sloping region of $\Delta R/R_0 = f(N)$. Thus, the critical value of the accumulated cyclic deformation in the specimen, at which the fatigue crack initiation occurs, is different for various levels of stresses. It is higher for larger stresses and lower for small ones.

Because the critical value of the accumulated cyclic deformation is different for various levels of stresses, it is possible to estimate the residual life of the specimens from the value of the accumulated cyclic deformation. It is possible to do this by studying the kinetics of the $\Delta R/R_0 = f(N)$ curves changes as well.

The use of (BiSb)Te films as fatigue gauges has great advantages. These gauges do not require any calibration of stresses acting on a construction in addition to knowledge of the exact number of cycles or the exact time of the active work under loading. They can be used in the temperature interval from -100 to $+60$ °C in any construction on which the spectrum of unknown load with a different amplitude, frequency

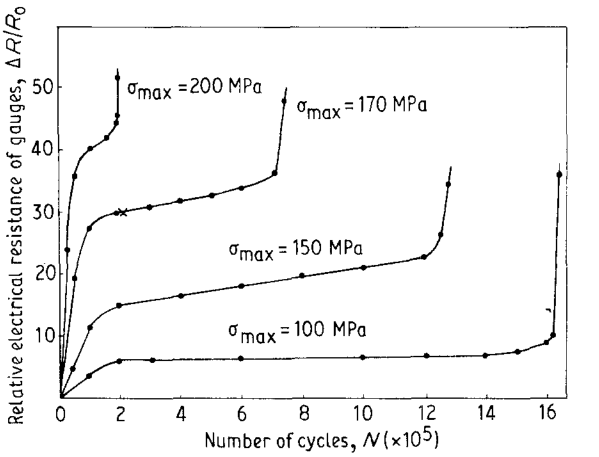

Figure 5 Variation of $\Delta R/R_0$ of the films with the number of cycles of the 2024T3 specimens at different maximum stresses of the cycle.

and duration attacks. It is well known that frequency has no influence on the process of fatigue, nor, therefore, on the process of cyclic deformation accumulation. Our experiments with 0.2 and 8 Hz confirmed this. The type of fatigue cycle has a weak influence on the value of cyclic accumulated deformation and on the form of the $\Delta R/R_0 = f(N)$ curves.

The suggested method consists in plotting $\Delta R/R_0 = f(n)$ during loading of the construction. Here, n is an ordinal number of measurement; it can be marked by the points on the abscissa in an arbitrary scale. It is necessary to perform $\Delta R/R_0$ measurements on a film from time to time after each stop during the active utilization of a construction, the completely unloaded state being obligatory. It is also necessary for the films to be cemented to the construction before beginning its usage or, at least, before 10^2 cycles of work.

The films give information only about those regions of the material which are beneath them. Therefore, it is very important in the preliminary work to determine the weakest places of the construction where initiation of fatigue cracks is most probable. It is possible to glue films over these places fully or partly, especially as the films can be of any reasonable size and form.

(BiSb)Te films are able "to remember" only the residual deformation which remains after removing the stresses, and they change their electrical resistance proportionally with it (see Fig. 2).

If during the employment of the construction its $\Delta R/R_0 = f(n)$ curve is plotted, then along the level of the third gently sloping region of the $\Delta R/R_0 = f(n)$ curve one can judge: (1) the average value of the stress spectrum acting on the construction, and (2) the average duration of the third stage of cyclic deformation accumulation, and hence, the remaining service life of the construction. It can be concluded from Fig. 5, where the duration of the third stage depends on the level of the $\Delta R/R_0 = f(n)$ curve at this stage, that the latter depends on applied stresses.

The accuracy of the estimation is obviously no worse than the value of durability spread for the σ_{max} tested. If it is possible to carry out enough check-ups, it will be possible to continue to use the construction up to the point of the inflection of the $\Delta R/R_0 = f(n)$ curve from the third region to the fourth. This inflection serves as an indicator which testifies to exhaustion of the construction life, i.e. that the critical level of accumulated cyclic deformation is achieved when the main crack begins to propagate in the material.

Thus there are two variants in the possible measurements. The weakest places of the construction are chosen and the films are cemented on them. In the first variant $\Delta R/R_0$ of the films is measured until the third gently sloping part of the $\Delta R/R_0$ curve, for example, at the point marked with a cross in the curve of $\sigma_{max} = 170$ MPa in Fig. 5, is achieved. Because the same levels of $\Delta R/R_0$ (levels of accumulated cyclic deformation) correspond to the same durations, the remaining service life of the place measured can be estimated and the final measurements can pay attention to the spread in durations. It is important to begin measurements in this case on a new construction. For the point marked with a cross, the remaining service life will be 5×10^5 cycles (Fig. 5).

The second variant foresees measurement of $\Delta R/R_0$ during the total stressing time until the beginning of the fourth stage, i.e. until a sharp increase of $\Delta R/R_0$ occurs. In the latter case any construction (new or used) can be measured. This latter variant is being employed for the estimation of residual service life of IL-62 soviet passenger jet aeroplanes. (BiSb)Te films were glued to the top wing panels of the five aeroplanes which had already logged 30000 flying hours. Measurements are being carried out regularly after every 300 flying hours. According to the measurements, all the points fall on the third gently sloping part of the $\Delta R/R_0 = f(N)$ curve. The tests will be carried out until the inflexion from the third to the fourth stage is achieved.

4. Conclusions

Cyclic deformation accumulation in the process of material fatigue is submitted to a particular regularity which allows estimation of the level of the cyclic stress spectrum and the remaining service life of materials at any moment of cycling.

Thin (BiSb)Te films can serve as the most suitable gauges of accumulated cyclic deformation, i.e. fatigue gauges.

Reference

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