PAPER REFERENCE: 1.3 16

EXPERIMENTAL INVESTIGATION OF THE LOCAL DEFORMATION PROCESSES IN JOINTS UNDER CYCLIC LOADING BY TRADITIONAL METHODS OF FATIGUE TESTING

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ABSTRACT

The task of calculation of joints fatigue life and their optimum design should be solved based on the analysis of local elasto-plastic strains. So it is necessary to overcome severe difficulties, arising from the considering the nature of contact interrelation and redistribution of residual stresses. The first of them is connected with the fact that the relation between local strains and local net **-** stresses is non-linear as a rule and sometimes, owing to physical and geometrical non-linearity of deforming process, it is expressed as hysteresis loops. Beside the local mechanical properties of a material in non-regular zones of joints change during loading and, generally, cannot be evaluated by tests of standard specimens. In this connection it can be concluded that the task of optimum design of joints cannot be solved without test data obtained by different methods of experimental mechanics.

INTRODUCTION

The activity was within the framework of the first stage of project □**808** ISTC "New Approaches To Predictive Joints Design Based On A Detailed Description Of Local Elasto-Plastic Strain History By Combining The Holographic Interferometry Data And Numerical Simulation" the main purpose of which is the development of a technique to calculate fatigue life of joints under non-regular cyclic loading.

The joints of different types are widely applied in engineering. In many cases they cause troubles in designs both from the view point of static, and fatigue strength. It is explained by the fact that the joints represent the most loaded structural items.

The reliable designing of joints based on life concept requires the analysis of a history of elasto-plastic deforming at cyclic loading and registration of actual nature of contact interrelation [1,2]. Higher level of confidence in defining of fatigue strength and durability at non-regular cyclic loading can be reached by taking into account the influence of the following factors:

- definition of changes in the stiffness of separate joint parts owing to local elasto-plastic deforming, that causes redistribution of loads and stresses, both between the joint parts, and in the region of main stress concentrators;
- installation of parameters for material local adaptivity expressed in the change of material mechanical properties owing to cyclic loading, and also registration of other factors, related with technology of manufacturing of joints.

The purpose of the given stage was improvement and development of techniques permitting to make the automatic data acquisition, processing and issue of reference data about the deformation characteristics both for joint parts (load - displacement relation of single fastener) and for structural materials for joint manufacture under cyclic non-regular loading.

THE EXPERIMENTAL TECHNIQUE

To have a capability to estimate joint life based on calculations of local strains it is necessary to receive experimental data about materials stress-strain curves, the data about the compliance of bolts and rivets and the hole deforming. The main methodical features of such experiment are:

- implementation of stress and strain controlled loading with programmed and quasi-random load sequences;
- registration of parameters of the cyclic stress-strain curve (axial stress, longitudinal and transversal deformations) at the lives up to 10^6 cycles at restricted capacitance of PC memory, and also time constraints assigned for recording;
- realization of experimental researches in frequency band from 0.1 up to **5 Hz** for the sin and triangular cycle shapes;
- maintenance and control of assigned accuracy within the limits of 1-2 %;
- automatic processing of the acquired data.

The basic technique of data recording at the research of generalised cyclic stress-strain curve in many cases is the xy-plotter record of stress-displacement relation. The disadvantages of this technique are obvious, as it requires practically constant presence of the operator, and besides it is difficult to record small changes of the charts, as in many cases they are superimposed against each other and at the subsequent analysis they practically cannot be distinguished. Therefore, it is quite natural to assign the task of data recording on a computer. Thus there is a problem of data recording algorithm. On one hand for data processing at elasto-plastic deforming it is necessary to have about 50 - 100 points per reversal for precise definition of the material characteristics in elastic and plastic areas and about 10 - 20 points at linear dependence between stresses and strains or deformations. At the life of 10^6 cycles and registrations along 3 channels (force, longitudinal and transversal strains) it would give rise to registration of $6 \cdot 10^7 - 12 \cdot 10^7$ points and 120 – 240 Megabyte on a specimen, that is not today possible due to economical reasons. In this connection the program of loading should be sectioned into stages, which can differ from each other only by the type of data registration in them. At the stages such as ***D*** (Detailed registration) the data recording is made at change of a signal absolute value on a selected level, and also at the moment of reversal beginning. At the stages such as ***S*** (Selected registration), the registration is made only at the moment of reversal beginning (at peak and valley values of a signal). The essential moment here is that the presence at such registration stages as ***D*** at the moment of reversal beginning allows acquiring maximum and minimum values of the signal in the reversal. Together with these registration types due to limitations in the volume of available memory there may be a necessity to inhibit data recording at some stages. For this case the stage such as ***N*** (No registration) is entered. This capability should be applied only to stages with small strains.

The correct combination of stages ***D*, *S*** and ***N*** allows reducing essentially the quantity of recorded data practically without any losses. It is suggested to pay the main attention to the unstable charts of stress-strain relation. They are characteristic for a static curve and initial stage of loading, after which their stabilization comes usually. When the drastic change of elasto-plastic material properties is expected, it is necessary to set the stages with detailed recording. If the change of properties is expected small or the values of strains lie in predominated elastic area, it is necessary to set the stages with selected recording. The detailed recording should also be done after a great number of cycles to have more valid data about elastic behaviour of a material. It is usually better to set a constant strain rate (triangular shape of a command signal) for detailed recording. The selected recording can be made at the sinusoidal shape of a command signal. The reason for such recommendation is that the plastic material properties can depend on the strain rate, while the elastic ones have no such dependence in a very wide range. At the same time at the sinusoidal shape of a command signal the accuracy of an electrohydraulic system is higher.

ALGORITHMS AND PROCESSING TECHNIQUE

For cycles with detailed recording of data about deforming the following ways of approximating were analysed:

$$\varepsilon = (\sigma/C_k)^{Cn} \tag{1}$$

$$\varepsilon = \sigma/E + (\sigma/C_k)^{Cn} \tag{2}$$

$$\varepsilon = \sigma/E + (\sigma/C_{k1})^{Cn1} + (\sigma/C_{k2})^{Cn2} \tag{3}$$

$$\varepsilon = \sigma/E + (\varepsilon_{0,2} - \sigma_{0,2}/E) \cdot [(\sigma-\sigma_e)/(\sigma_{0,2} - \sigma_e)]^{Cn} \tag{4}$$

Where σ, ε – stresses and strain which are read from the point of reversal beginning, that is double amplitude of stresses and strain;

E – Young modulus;

C_k, C_n, C_{k1}, C_{n1}, C_{k2}, C_{n2} – constants;

$\sigma_{0,2}$ ($\varepsilon_{0,2}$), σ_e – yield strength (strain) and elastic limit respectively.

Eqn. 1 is used for calculations in the field of low-cycle fatigue [3 – 4]. The main advantage of this formula is that it enables to get the solution of a system of non-linear equations dealing with local stresses and strains according to the approximated formulae in the analytical form. At the same time the absence of a linear part in this formula leads to considerable inaccuracies in defining elastic deformations, that does not match the purposes of this presentation.

Eqn. **2,** also known as the Ramberg-Osgood Eqn. 5, is widely used in many publications, in particular, it was used for generalising the data for calculation of the local stress-strain state in [6 – 9]. Unlike the Eqn. 1, this one as well as Eqns. **3** – 4, allows to get the solution of a system of non-linear equations dealing with local stresses and strains only by numerical methods, but at computer processing this disadvantage is not so relevant. At the same time the presence of a linear part in this formula allows considerably to increase the accuracy of determining elastic strains. The approximation of stress-strain curves for aircraft aluminum alloys being performed in this presentation, demonstrates that in the transient area from elastic to plastic strain the considerable deviations of experimental and analytical points based on Eqn. **2** are observed (Figure 1).

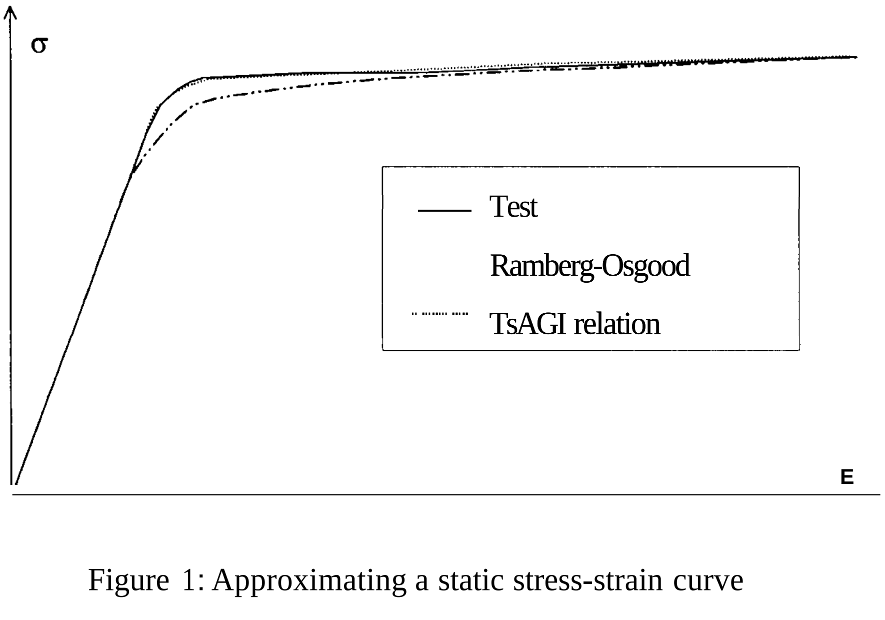

Figure 1: Approximating a static stress-strain curve

Eqn. 3, used, in particular, for approximating the stress-strain curves in [10], as demonstrated by the analysis, at approximating often results in the constants C_{k1} and C_{k2}, C_{n1} and C_{n2}, that are close to the value that is this approximating practically coincides the approximating according to Eqn. **2.** At the same time it is difficult to avoid poor approximating in the transient area from elastic to plastic strain while using it. Apparently, its applying is justified only in the case, when the stress-strain curve should be approximated in a very large range of strains, that is not the actual task for the purposes of this presentation.

Eqn. **4** was originally proposed in TsAGI by O.Bankina to approximate static stress-strain curves. It is applied to approximating in the plastic area (at $\sigma \geq \sigma_e$). The elastic limit σ_e is assumed to be the stress corresponding to the plastic strain value equal to 0,01%. In many respects one of the main purposes of its development was the desire to avoid the necessity to get experimental points of the stress-strain function for representation of stress-strain curve in the analytical form. Therefore the pattern of this formula was oriented on the usage of constants, which are included practically in all reference books on material properties, namely Young modulus E, yield strength $\sigma_{0,2}$ and elastic limit σ_e. Constant C_n may be determined such a reference point as the strain at the moment of reaching the ultimate strength. It is better to determine constant C_n in this presentation using the point corresponding to the deformation in the range from 2% up to 5%, or by the average of slopes corresponding to the points, lying in the plastic area, that correlates with the method of the least square being applied. In the latter case definition of constant C_n is made by the formula:

$$C_n = \frac{\sum_{i=1}^{N} \frac{\log \varepsilon_{p_i}}{\log S_i}}{N} \qquad (5)$$

Where $\varepsilon_{pi} = \varepsilon_i - \sigma/E$ – plastic strain;

$S_i = (\varepsilon_{0,2} - \sigma_{0,2}/E) \cdot [(\sigma_i - \sigma_e)/(\sigma_{0,2} - \sigma_e)]$;

i – index meaning the number of a point;

N – quantity of experimental points in the plastic area.

As it is obvious from Figure 1 applying of Eqn. **4** gives good approximation of the whole stress-strain curve, including the transient area from elastic to plastic strain. Thus, it is possible to draw a conclusion that the application of Eqn. **4** gives the best results at approximating both static, and cyclic stress-strain curves for the tasks of calculation the joint lives under non-regular cyclic loading based on the regard for kinetics of a local stress-strain state in the zone of potential fatigue failure. The additional advantage of Eqn. **4** is the capability to describe the stress-strain curve using standard reference material properties: Young modulus, elastic limits, yield strengths, ultimate strengths, etc.

The cycles with selected stress-strain recording that have only initial and final point recorded, are processed to get the following data on process: of Young modulus variations (secant module, in general) and possible relaxation of the cycle mean stresses.

RESEARCH OF LOAD - DISPLACEMENT RELATION OF BOLTS AND RIVETS.

The load - displacement relation of fasteners in most cases is the dominating one to analyse the joint stress state. The accuracy of calculation depends also on the accuracy of its definition. There were many attempts to outline the load-displacement relation by analysis, however, numerous factors that are difficult to calculate, but having some effect on the fastener joint strains do not allow to remain exclusively on the basis of theoretical considerations. Therefore, most valid data are obtained by experiments. From the analysis of the experimental data, obtained by us, and other research devoted to this problem it is possible to conclude that the load - displacement relation in the general case when the fastener is inserted without interference or clearance has a view shown in Figure 2. The chart in Figure **2** can be arbitrarily sectioned into three parts:

U-A – the effort is transmitted both through the fastener, and through the contact area of the joined elements due to the forces of friction;
A-B – when the force of friction becomes critical all the additional load is transmitted through the fastener;
B-C – it is characterised by initiation of plastic strains in the joint elements. During the subsequent cycles of loading the chart (Figure 2) will have the view of hysteresis loops.

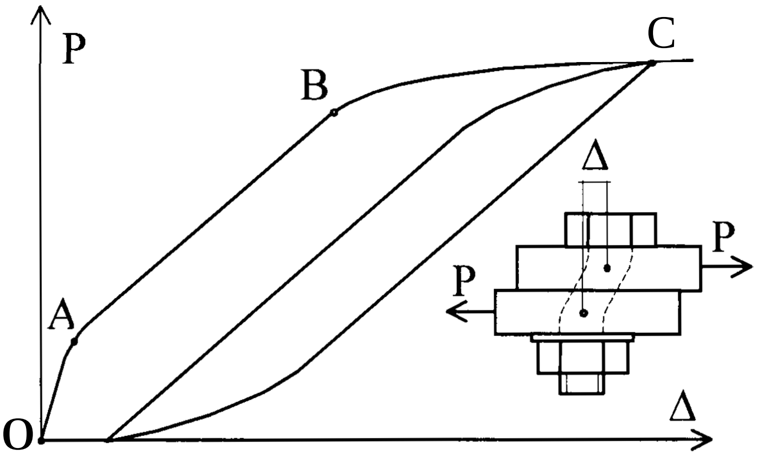

Figure 2: Relation of bolt joint displacement vs the applied load.

Thus, the non-linearity in load - displacement relation of the fastener is already observed at the initial stages of loading. This non-linearity in the compliance of bolts and rivets in multi-row joints can results in noticeable load redistribution along the fasteners, that should be, as the experience demonstrates is necessary to be taken into account during life calculation.

RESEARCH OF FREE HOLE STRAIN

To refine and improve the criteria for crack initiation process much attention should be paid to the study of local cyclic strain at the stage of macro-crack generating and initiating. The interferometric holography method allowed to study some laws for the initial stage of local cyclic strain. The research was performed on the specimen with a free hole made from 1163□ aluminium alloy 60 mm wide, 260 mm long, 6 mm thick and having the hole radius 6 mm. The tests program consisted of 1418 cycles of loading with maximum tension and compression nominal gross stresses G,, $= 225{,}4$ MPa and $\sigma_{min} = -127{,}4$ MPa, respectively. (Experiments were carried by Dr. V.Gorodnichenko).

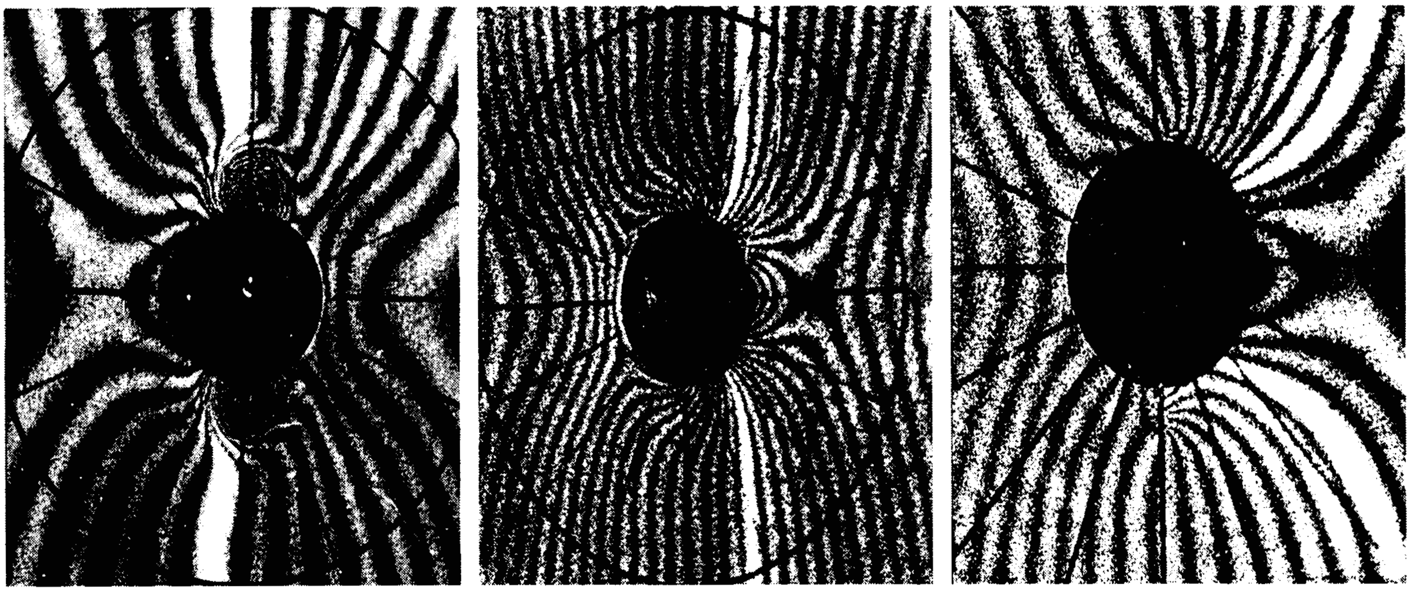

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Figure 3: Picture of fringes at the stage: (a) initial, (b) stable cyclic strain, (□) of crack initiation.

At the initial stage of loading (the first cycle) and in the field of stable local cyclic strain the general feature is that the interference fringes are either continuous, or expand to the hole contour (Figures 3a and 3b). Quite different picture appears when a fatigue crack is initiated when the gaps in several interference fringes in the vicinity of points with maximum strains on the hole contour (Figure 3c) are clearly seen. At the negative stress values the crack is closed, and the destruction material being monolithic does not affect the picture of interference fringes.

The obtained qualitative data that allow estimating the number of cycles before originating of a fatigue crack have also quantitative validation. The relation of strain $\Delta\varepsilon_x$ double amplitude on the hole contour vs the number of loading cycles N is given in Figure 4. Here it is possible to dedicate some typical parts. After stabilisation of strain double amplitude at the initial stage there is some increasing in $\Delta\varepsilon_x$ magnitude at the expense of ε_x negative values (cycles 218 – 1 017). The crack initiation is connected with noticeable $\Delta\varepsilon_x$ increase (cycle 1418). And, the increasing of $\Delta\varepsilon_x$ magnitude is connected with the increment of strain in the tension reversal.

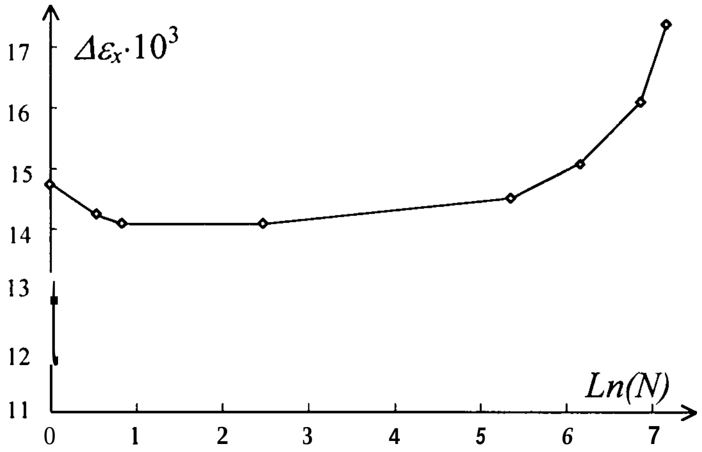

Figure 4: Relation of double amplitude of maximum strains on the hole contour vs the number of loading cycles.

The introduced material indicates a capability to fix the moment of crack initiation using the quantitative characteristics of parameter change due to local strain.

As the method of interferometric holography is rather labour-consuming and consequently it is hardly suitable to define maximum strain in a large number of experiments it is possible to use the method, based on measurement of change in the mutual location of the points, lying on the hole diameter parallel to loading axis. The approbation of this method was carried out on a specimen with a free hole made of 1163□ and □95pch□□ aluminium alloys. The specimen geometrical sizes together with the value of central hole diameter are presented in Figures 5 – 6. The tests were conducted on the electrohydraulic machine using pulsating cycles (□95pch□3 specimen at net stresses σ_{max}= 176,4 MPa; 1163□ specimen at σ_{max}= 196 MPa).

To record the displacements (strains) the gauges should satisfy the following requirements:

- continuous record of strain under the action of several millions of loading cycles on the specimen. Thus the calibration relations of the strain gauge should not change considerably;
- the reliability of gauge attachment to the specimen, that is determined by small weight, the effort of forcing the members of gauge against the specimen, except slipping etc;
- low loading of all strain gauge elements. Low loading is assumed when maximum stresses of material fatigue strength are not exceeding limiting fatigue stresses of a material;

- measurement of displacements near structural irregularities of an arbitrary type (free hole, bolt or rivet joint, weld joints etc.) and size. Therefore, a capability of in-time changes in the strain gauge design should be envisaged;
- there should be some protection against mechanical damages.

The strain gauges satisfying the indicated requirements have been designed and manufactured.

This gauge also can be used to find out the moment of fatigue crack initiation under cyclic and quasi-random loading (like the crack measurement in the crack opening displacement method). In order to get a relation between lengths of crack and gauge readings, test breaks at different gauge signals were used. To stop the tests at the increase of the maximum signal from the strain gauge the limit detector was used. When the crack has grown up to the selected signal level proportional to hole diameter change **Ad** + Δd_{crack} (where **Ad** – a change of hole diameter due to the maximum load, Δd_{crack} – a change of hole diameter at crack initiation) the tests were stopped, and the specimens were broken by static load.

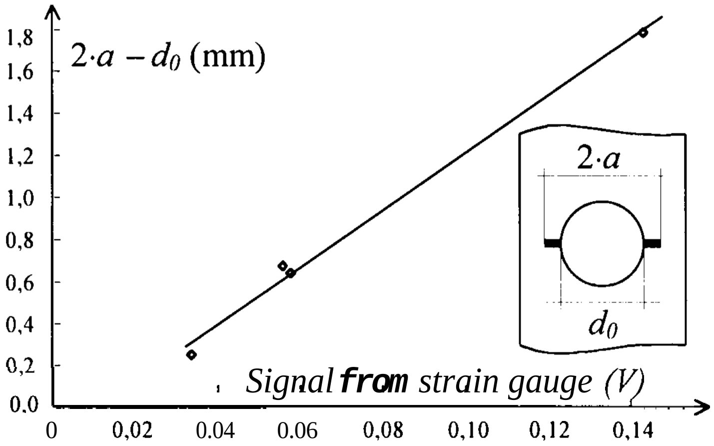

Figure 5: Relation between surface crack length and increment of a gauge signal (hole diameter change) in □96pch□3 specimen.

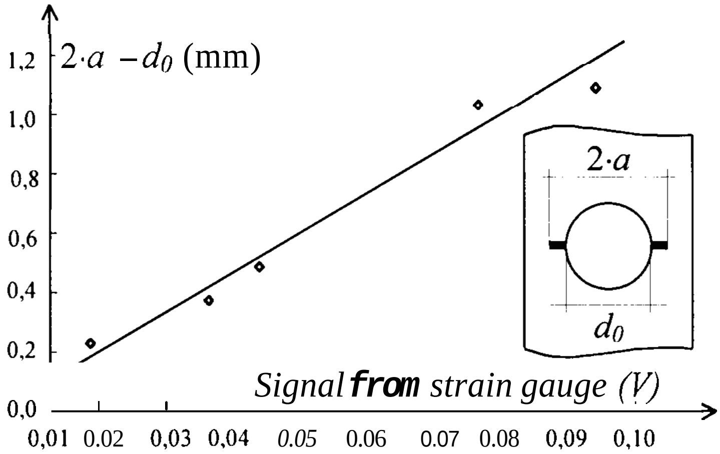

Figure 6: Relation between surface crack length and increment of a gauge signal (hole diameter change) in 1163T specimen.

Based on the measurement results for the hole diameter the relation has been deduced between fatigue crack length ($2 \cdot a - d_0$), when the crack has come to the surface and located on the specimen side, where the strain gauge was mounted and value of Δd_{crack} (Figures 5 and 6). It has appeared that these data are well approximated by linear dependence with correlation coefficient 0.989 for □95pch□□ and 0.964 for 1163□. Thus, the study results for □95pch□□ and 1163□ specimens about 3 mm thick have demonstrated, that there exists some linear dependence between surface crack length up to 2 mm (the crack is not through thickness one) and change of hole diameter, which can be used to define the growth rate of small cracks.

CONCLUSIONS

- The technique of data recording has been proposed for research of the cyclic stress-strain properties, whose application will allow to reduce considerably the extent of the information, recorded during the experiment;

- The description of the stress-strain curve using the relation, developed in TsAGI, gives the best fitting for both static, and cyclic curves and it allows to receive its analytical presentation using some standard reference characteristics: Young modulus, elastic limits, yield strength, ultimate strength, etc.;

- The load - displacement relation of bolts and rivets has a clearly seen non-linear pattern in the whole range of load change and under cyclic loading it gains the form of hysteresis loops. This non-linearity of a compliance in bolted and riveted multi-row joints can result in load redistribution along the fastener, which, as experience demonstrates is necessary to be taken into account during life calculation;

- By comparing with measurement results for strain fields using methods of interferometric holography it is shown that the change in the hole diameter along the axis parallel to the direction of force application determinates maximum strain on hole contour with proper accuracy. Thus the measurement of this hole diameter using the developed strain gauges allows to study the strain kinetics in the concentration zone under non-regular cyclic loading during a great number of cycles and to make result processing much more easier;

- It is shown that there exists some linear dependence between the length of a surface crack up to 2 mm (the crack is not through thickness one) and the change of the hole diameter along the axis parallel to the direction of force application which can be used to define the crack initiation moment and growth rate of small cracks.

ACKNOWLEDGEMENTS

Part of the present work was supported by the ISTC. The authors acknowledge their sponsorship and appreciate the grateful co-operation of Project Manager Dr. V. Pisarev of TsAGI, Dr. V. Gorodnichenko and their TsAGI colleagues during this research.

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