The Stress-Strain Condition Estimation of Detail in Crack Tip by Integral Strain Gauges

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Abstract. The paper considers the task of stress-strain condition calculation of experimental sample in fatigue crack tip on weld boundary at its cyclic deforming. For this task decision authors use the information obtained by original means of cyclic strains measurement: Integral Strain Gauges. The results of carried experimental researches are compared with data of stress-strain condition estimation of detail in crack tip calculated by Finish Element Method.

Introduction

There are presented in works [1, 2, 3] the methods of experimental estimation of strains and stresses, appearing on details surfaces at cyclic loading. These methods are based on new means of measurement – Integral Strain Gauges (ISG). It considers the gauge manufacture technology, the ways of obtaining information by gauges and data processing methods, allowing to estimate the loading, to calculate the longevity and to forecast the resource of machine parts and metalware at block and casual loading modes in conditions of stand and operational tests. The monograph [3] describes the methods of Integral Strain Gauges applications for experimental research of parts of transmissions and carrying systems of transport machines.

Accumulation of fatigue damages in process of cyclic deforming of detail leads to crack initiation, appearing as usual in stress concentration zone. At further cyclic deforming of detail the microcrack grows to macrocrack, which causes detail destruction [4, 5]. For estimation of fatigue crack growth rate it is necessary to determine the parameters of fracture mechanics, which can be calculated by computer simulation. Now for the solution of this task the Finish Element Method [6, 7, 8] is widely used. At the same time for correct use of simulation results it is necessary to have the data of its comparison with actual stress distribution law in crack tip. ISG pasted to the detail surface with crack allows to obtain the demanded data. The goal of described research was determination with the help an ISG the stress-strain condition of detail in the fatigue crack tip on weld boundary at its cyclic deforming. For this task decision authors carried out both experimental research using ISG and Finish Element Analysis by software ANSYS [8, 9, 10, 11] for the determination of strain distribution law in crack tip.
1. Experimental researches
The welded samples (Figure 1) made of a welded pipe were object of the experiment. Pipe material: 14HGS. Weld was placed on a middle part of a sample perpendicular to its longitudinal axis. ISG being the aluminum foil made on special technology [1, 3] was pasted to the sample face. The sample on a pulsating stand was subjected to deforming in the conditions of stretching at constant amplitude ($F_{\text{min}} = 6000$ N, $F_{\text{max}} = 35000$ N) during 80 000 cycles. During last 20 000 cycles the sample had crack. By photo equipment the digital pictures of ISG reaction on a face surface of welded sample (Figure 2), on the top surface of weld and on the lower surface of weld (Figure 3) were obtained. The analysis of the achieved information provides that intensity of ISG reaction in various zones of a weld significantly differs. The greatest ISG reaction is registered on a surface of the lower weld on weld boundary (Figure 3а). The maximum ISG reaction testifies to stress (strains) concentration in the researched place and, accordingly, the greatest accumulated fatigue damage. Confirmation of described fact is fatigue crack initiation on a welded sample in a zone of weld boundary of the lower weld with the main metal (Figure 3а). The obtained photos of ISG reaction (similar to data of work [12] show that stress distribution (accumulated during cyclic deforming of a sample) on a surface of a welded sample in its different zones (weld, zone of thermal influence, main metal, weld boundary) is very heterogeneous. The area in crack tip is characterized by still grated heterogeneity of stress distribution. Figure 4 illustrates the reaction of ISG placed on a sample face (Figure 1) in a location of the crack initiation (on the weld boundary).

![Figure 1. a) The welded sample with ISG; b) face-grind of welded sample](image-url)
Figure 2. The ISG reaction on different face sites of welded sample:
a) the top weld in a weld zone with the main metal; b) the lower weld in a zone of thermal influence;
c) the lower weld in a weld zone with the main metal

Figure 3. An ISG reaction after weld sample deforming during 60000 cycles:
a) on a surface of lower weld in zone of weld boundary; b) on a surface of main metal (top surface of a sample); c) on a surface of main metal (lower surface of a sample)

Figure 4. The reaction on ISG surface in crack tip
For an explanation of the obtained picture it is necessary to determine what deformations correspond to borders of ISG reaction. In the book [3] at research of load distribution in Novikov's gearing with the help an ISG it was established that ISG reaction border corresponds to compression strains of a constant value. For the purpose of verification of this assumption the stress-strain condition calculation of sample with crack was executed for identification of a picture of Figure 4.

2. Theoretical researches by the Finish Element Analysis

For the solution of a task the sample (Figure 5a) was used. Because of symmetry of a sample about two planes, only ¼ part of sample was subjected to the analysis. The calculation model of sample loading is submitted on Figure 5b. The task was solved by program complex ANSYS [9, 12].

![The sample and its loading calculation model](image)

a) the geometrical description  
b) finish element model

**Figure 5.** The sample and its loading calculation model

The geometrical model was constructed taking into account possibility of calculation of destruction mechanics parameters: near crack tip field the auxiliary areas outlined by arches for generating in crack tip the singular elements were created. The areas defining the top side of a sample were meshed by two-dimensional quadratic finish elements. Around the crack tip the triangular degenerate singular elements with the intermediate nodes shifted on ¼ towards tip were created. Such elements allow to describe correctly stress surge in crack tip [8]. Other elements are set by the square quadrangular. As a result of extrude operation the three-dimensional quadratic elements in whole sample volume were generated.

On the section planes of sample the symmetry boundary conditions were defined (nodes with zero degrees of freedom are shown in Figure 5b by labels). Pressure 100 MPas modeling stretching of a sample and similar to the carried-out experimental researches was applied to a side surface of model. For the solution of this task the Sparse Solver was chosen. This solver is used in ANSYS by default.

After the solution is done it is possible in ANSYS to plot the results - standard physical quantities, such as displacements, strains, stresses and others. However for interpretation of ISG reaction it is necessary to have pictures of compression strains which aren't present in the ANSYS results list. The special macro [8] in the ANSYS Parametric Design Language realizing operations with arrays of element tables [13] was developed for creation of a compression strains distribution picture in this paper.

As a result of the executed computer simulation the pictures of compression strains in crack tip of a sample (Figure 6) are obtained which form is sufficiently close to the registered ISG reaction (Figure 4).

For comparison, Figure 7 illustrates the picture of distribution of equivalent stresses von Mises [14] near crack tip (standard result in ANSYS) which shows very high stress concentration in crack tip. The deformed shape of models shown on figure 6 and figure 7 is exaggerated by 50 times for visualization.
Two parameters are necessary for the analysis of crack growth: coefficient of stress intensity $K$ and invariant $J$-integral [5, 15]. As shown in [8, 15], crack opening arises if $K$ exceeds maximum limit. In case of the solution of an elastic task the value of $J$-integral is necessary only for more precise definition of $K$.

In this analysis for determination of the $K_I$ – coefficient of stress intensity [15, 16] for a separation crack the KCALC command of an ANSYS was used, and for calculation of $J$-integral the special macro in the APDL-language was used [8]. As a result of calculations the following values were obtained:

$$J = 5621.12;$$
\[ K_I = 34.752 MPa \sqrt{m} \quad \text{in accordance with the method of displacements;} \]
\[ K_I = 36.05 MPa \sqrt{m} \quad \text{in accordance with the method of J-integral.} \]

The divergence in 3.6% in results of calculations of \( K_I \) by two different methods is very small and quite allowable.

**Conclusion**

The proposed computational-experimental method allows with sufficient degree of reliability to estimate the values of parameters characterizing the process of crack growth and appearing in equations for durability estimation and lifetime calculation of metal manufactures.

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