Applications of fatigue gauges for detection of subsurface cracks and defects

S G Tyutrin
Kurgan state university, 63/4, Sovetskaya street, Kurgan, 640020, Russia

E-mail: kgu_sm@rambler.ru

Abstract. The possibility of using fatigue gauges to detect cracks and crack-like defects that occur at some depth in the specimens was investigated. Industrial tin foil with additional annealing was used. Subsurface cracks were modeled by cross drilling followed by cutting with steel wire. The distribution of appearing stresses under the action of static load was estimated by the finite element method. In the presence of a subsurface crack, the first manifestations of fatigue damage on the gauge surface are observed in two zones located from the dangerous section at a distance approximately equal to the depth of the crack. This allows not only to diagnose the presence of cracks and similar defects, but also to determine the distance from the top of the crack to the surface of the specimen.

1. Introduction
Subsurface cracks and defects are a common cause of loss of product performance in various fields of technology.

"Subsurface damage is easily induced in machining of hard and brittle materials because of their particular mechanical and physical properties" [1]. Subsurface cracks in continuous cast steel products were formed due to the predominant segregation of sulfur, copper and the subsequent formation of various types of sulfide inclusions [2]. Subsurface cracks are one of major failure modes of roller bearings due to fatigue under periodic contact forces and external impulse loads [3]. Subsurface cracks in gear teeth and the lubricating oil that has penetrated them, during operation cause spalling of the material on their surfaces [4].

There are many methods for detection of subsurface cracks and damages. They are classified into two categories: destructive and non-destructive. Destructive methods include traditional taper polishing, dimpling, bonded-interface technique, cross-sectional microscopy, transmission electron microscopy, chemical etching and other. The destructive methods are relatively reliable, but they are time-consuming, which reduces production efficiency and increases cost [1].

Non-destructive methods include optical coherent tomography, laser scattering, scanning acoustic microscopy, X-ray diffraction method, X-ray computed tomography, micro-Raman spectroscopy, eddy current detection, magnetic Barkhausen noise detection technique and other. The non-destructive methods preserve parts and save time, which is in favor of improving overall manufacturing efficiency [1].

For the first time, the non-destructive method for subsurface crack detection in metallic and non-metallic materials based on using of fatigue gauges was briefly presented by author in [5]. Present article describes the details of this method.
2. Materials, methods and results of the experiment

The appearance of subsurface cracks and defects in the loaded part leads to an increase in stresses on its surface. The use of copper [6-8] and aluminum [9-12] fatigue gauges for determining cyclic stresses on the surface of machine parts is widely known. For this purpose, a large number of techniques and devices have been developed [13]. Thus, when working with fatigue sensors, almost all known methods of non-destructive control [1] are successfully used. Optical methods for monitoring fatigue gauges are the most widely used, since the observed changes in their surfaces during cyclic deformations are quite large.

The principles of operation of fatigue gauges were described in [14]. Also in this paper, a method for synthesizing highly sensitive fatigue gauges was presented. Based on this approach it was proposed to use indium and stannum for the manufacture of fatigue gauges. It is experimentally confirmed [15, 16] that fatigue gauges made of indium or tin foil have significantly higher sensitivity than known gauges.

Tin foil of industrial production was used in the work. It manufactured according to the Russian standard GOST 18394-73. According to this standard, tin foil is made of an alloy of stannum with antimony, in which antimony is 1.9-3.1 %. Foil thickness was 20 µm. In addition, this foil was annealed at a temperature of 200-203 °C for 10 hours. After that, the foil was polished and cut into gauges. Adhesives based on polychloroprene or cyanoacrylate were used to attach fatigue gauges to test specimens.

Specimens with a square cross section 11.3x11.3 mm of the working part were used (figure 1). A hole with a diameter of 1 mm was drilled to simulate a subsurface crack. The hole was located in the cross section of the specimen in a direction parallel to the controlled surface. After that, using a steel wire with a diameter of 0.4 mm, an incision was made in the cross-sectional plane of the specimen (figure 2).

![Figure 1. Test specimen.](image1)

![Figure 2. Hole-simulator of a subsurface crack.](image2)

The test specimens were made of steel E 235-C (Fe 360-C) ISO 630:1995. The tests were carried out according to the scheme of rotation bending load [17]. The frequency of specimen rotation was 3.33 Hz.

As a result of experiments, it was found that in the presence of a subsurface crack, the first changes in the surface relief of the fatigue sensor are observed simultaneously in two zones (figure 3). These zones are located near the dangerous section at a distance approximately equal to the depth of the
crack. This allows not only to diagnose the presence of subsurface cracks and similar defects, but also to determine the distance from the surface of the specimen to the top of the crack.

![Image](image1)

**Figure 3.** Observed changes on the surface of the tin fatigue gauge to the left and right of the dangerous section: a – overall appearance; b – with 28x magnification.

As the specimen continues to be tested, the areas of visible changes on the sensor surface increase. However, the contrast of the observed changes is reduced.

3. **The results of a computer analysis**

The analysis of the obtained experimental results was performed using computer modeling by the finite element method. The plane stress state was considered. Quadratic triangular elements were used.

Figure 4 shows the calculated distribution of stresses occurring in the specimen near the subsurface crack. In figure 4, two stress peaks are clearly visible, located to the left and right of the dangerous cross section. This explains the distribution of observed changes on the surface of the fatigue gauge (figure 3).

![Image](image2)

**Figure 4.** Calculated distribution of stresses occurring in the specimen near the subsurface crack: a – inside the specimen; b – on the surface of the specimen.

The finite element method was used to study the stress distribution on the specimen surface in the presence of various subsurface cracks. Equivalent stresses were determined, for which the Mises theory was applied. During the study, the length of the crack varied: $\ell = 0.5 \ldots 2$ mm. The depth to the crack top also varied: $\Delta = 0.5 \ldots 1.5$ mm. The calculation results are shown in figure 5.

Additionally, the influence of the depth of the crack top location on the value of the stress peak offset from the dangerous cross-section was studied. In the studied range of parameters, the obtained dependence is close to the form $x = \Delta$ (figure 6): the value of the displacement of the stress peak from the dangerous cross-section is approximately equal to the depth of the crack top location.
Using the finite element method, it is possible to provide high contrast of the observed changes on the surface of fatigue gauges over a long period of their operation. This is convenient for practical use, since it does not require too frequent inspection of the gauge surface. This goal can be achieved if the following two conditions are met:

1) the stress value that occurs on the monitored surface in the absence of subsurface cracks and defects is close to the limit of the fatigue gauge sensitivity (a large number of loading cycles will be required for the reaction to appear on the surface of the fatigue gauge);

2) the values of the maximum stresses that occur on the controlled surface when a subsurface crack appears are large enough (they quickly lead to visible changes on the surface of the fatigue gauge used).

In real operating conditions this is ensured by selecting a fatigue gauge with the appropriate properties.

**Figure 5.** The dependences of the surface stress $\sigma$ on the distance $x$ to the dangerous cross-section at different crack lengths $\ell$ and depths $\Delta$ to its top: a – $\Delta=0.5$ mm; b – $\Delta=1$ mm; c – $\Delta=1.5$ mm.

**Figure 6.** The influence of the depth of the crack to its top $\Delta$ on the distance $x$ from the dangerous cross-section to the point of the surface with the maximum stress.
In the conditions of the experiment, the high contrast of the observed changes on the surface of the tin fatigue gauge was provided by selecting the value of the applied load. In the absence of a subsurface crack, the stress amplitude on the specimen surface was 30 MPa. In the presence of a subsurface crack, the stress amplitude on the specimen surface increased to 74.85 MPa, which was determined by the finite element method.

4. Conclusion

The presence of subsurface cracks and defects can be diagnosed using fatigue gauges with suitable properties.

Fatigue gauges allow estimating the depth to the top of the subsurface crack.

The use of fatigue gauges does not require large financial investments, so this method is suitable for use in low-budget enterprises, for example, in farms.

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