Determination of macro-stresses in half-cycles of thermal fatigue tests

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Abstract: The published results of thermal fatigue studies, which also included metallographic observations during the tests, are analyzed. All tests were performed on flat corset samples, in which, as in products, the plastic deformation ($\varepsilon_{pl}$) in the cycle can vary widely. In addition, they allow you to vary the $\varepsilon_{pl}$ by changing the parameters of the sample shape. A method and device for determining the tensile stresses in the cooling half-cycle in tests on corset samples are proposed and tested. They are an important parameter, as they control the formation and growth of cracks in the material of products during the development of thermal fatigue.

1. Introduction

Thermal fatigue is a serious problem for industrial products, the parts of which experience regular heat changes during usage. Presently, the situation is particularly relevant since there is a tendency to increase the temperature conditions during operation and, accordingly, to expand the temperature range when entering different modes. However, in recent decades, interest in the study of thermal fatigue has sharply decreased. This can be observed through a decrease of publications on this subject in the Russian scientific press. A plausible hypothesis for this phenomenon could be that it has ceased to be considered as a factor when evaluating the resource of products. Apparently, this is due to the fact that the data on the durability of materials obtained in tests, mainly by the Coffin’s method on samples of special shapes [1-4]. These tests differ significantly from those that characterize the development of the destruction process in the hazardous areas of real products.

Thermal fatigue, as a phenomenon of destruction of products that occurs as a result of cyclic heating, includes a stage called damage accumulation, in which irreversible changes in the substructure of the material occur under the influence of plastic deformation. This leads it to a state favorable for the formation of cracks, followed by a stage of destruction [1, 3, 5]. During use such a development of the process is favored by the unevenness of the cross sections and as result, the unevenness of the changing temperature of the product, which is periodically heated. As a consequence for the local zones, there is a constraint of free thermal deformation, which is accompanied by the appearance of elastic deformation and stresses that initiate the formation and development of main cracks. In this regard, it is of interest to study the dynamics of stress changes in half-cycles of thermal fatigue tests and their measurements were performed in most thermal cycling tests. However, they were usually produced not on the sample itself, but using parts of the loading devices of the test equipment that interact with the sample (rods, membranes, etc.). In some cases, the reliability of the published results is questionable [6-10]. In the tests conducted on the samples of the
corset form, it was not possible to measure the stresses [11-16], although the development of thermal fatigue in them is more consistent with what is happening in real products. The question of the magnitude of stresses in the corset samples requires special attention, and in this regard, this development was undertaken.

2. Method and device for determining macro-stresses in thermal fatigue tests on corset form samples

Regardless of whether the stresses (σ) are determined by X-ray or mechanical methods, the elastic strain (ε_{el}) corresponding to the stress level, which, according to Hooke's law, is proportional to it, must be measured experimentally. In the study of thermal fatigue, which is performed by means of thermocyclic tests, elastic deformation is a means of compensating for constrained free thermal deformation. Its manifestations directly on the sample are absent and their mechanical measurement is not feasible. When removing the constraint by unloading the sample, the elastic strain changes the size of the sample and can be measured; however this procedure is not desirable in the course of ongoing tests.

The determination of stresses in half-cycles of tests by the X-ray method is possible, but it is associated with technical difficulties. Nevertheless, the radiographic determination of the stresses in the half-cycles of cooling of thermocyclic tests is practically possible. To do this, it is proposed to use a small-sized device for cyclic heating of a confined sample (Figure 1). The device can be installed to perform X-ray photography in one of the available or in a modified goniometric prefix of a serial diffractometer. Such measurements are very important, since there is reason to believe that the tensile stresses in the products that appear due to the constraint of thermal deformation during their cooling are crucial in the development of destruction.

The device for thermal loading of the corset sample is made in the form of a removable autonomous unit and consists of a frame 1 and a platform 2 movable relative to it with a rod 3. A pressure nut 6 is screwed on the output end of the rod, equipped with a thread. The plane of the sample 5, fixed on the axes 4, is located parallel to the base of the frame. The nut 6 serves to create a constraint of free compression of the sample 5 during its cooling period (a half-cycle of cooling). The platform 2, the stem 3 and the nut 6 are electrically insulated from the frame 1 with mica gaskets. To heat the sample, copper busbars of the electric voltage supply are screwed to the frame 1 and to the end of the rod 3. After heating the sample to a specific temperature (measured by a thermocouple welded to it in the center), the pressure nut 6 is wrapped up to the stop. This provides a rigid constraint of the free thermal deformation of the compression of the sample during the subsequent cooling, which leads to the appearance of elastic deformation and tensile stresses. The unit, cooled to room temperature, is released from the tires connected to it and is ready for X-ray shooting. After completing the measurements, which are performed by the well-known "method-sin^2ψ" [17 - 20]. The unit is returned to the heating station to continue thermocyclic tests. Subsequent measurements are taken after a given number of cycles according to the provided program.

![Figure 1. Autonomous loading unit with a corset sample.](image_url)
The operation of the device is illustrated by the example of the determination of macro-stresses in the heat-resistant alloy EP741. This alloy is used in the aircraft engine industry in the manufacturing of parts subjected to cyclic heating during operation. As an example, the results of measurements performed on flat corselet samples with a thickness of 3 mm are given (Figure 2). The etched surface of the sample was marked in the form of strokes (through ~4 mm). The strokes were served to determine the deformation and the subsequent calculation of stresses, in order to compare with the data obtained by the X-ray method. The prepared sample was fixed in the loading device and remained in it during all further actions (loading, radiography, unloading, and measurements).

![Figure 2. A flat corset sample with a marking for measuring deformity.](image)

Initially, an X-ray survey was carried out in the center of the prepared samples. Measurements and calculations were performed, provided by the program of the method \( \sin^2 \psi \), which showed that macro-stresses in the material in the initial state are not detected.

The ready-to-use loading device with the sample was fixed on the table of the IMASH-65 thermal cycle testing unit. The rod 3 and the frame 1 were connected to the power supply of the installation and an electric current was passed through the free sample. Heating was carried out to temperatures \( T_{\text{max}} = 600 \) and \( 900^\circ C \) in the central part of the sample L (2-3), where a thermocouple was welded. The difference in the specified temperatures between the center and the marks 2 and 3 did not exceed 4-5\(^\circ C\). After setting the temperature, the distance between the labels was measured, and the thermal elongation (\( \Delta l_{\text{free}} \)) of the areas of interest was determined, which was compared with its calculated data. The value of \( \Delta l_{\text{free}} \) at the specified \( T_{\text{max}} (600 \) and \( 900^\circ C) \) in the section L (2-3) with a length of \( l_0 = 4 \) mm was 0.032 and 0.053 mm, respectively. Then, to create tightness, the nut 6 was wrapped up to the stop and after turning off the heating, the sample was cooled to room temperature. Subsequent measurements showed that \( l_0 \) decreased by 0.009 0.014 mm when cooled from a temperature of 600 and 900\(^\circ C\). This indicates that the system does not completely constrain the thermal deformation of the \( l_0 \) section due to the insufficient rigidity of the sample shoulders and its heads.

After that, the block with the sample in the loaded state was installed in the goniometric attachment (Figure 3) of the DR "Promcontrol" diffractometer used in the work, and X-ray measurements were started.

The series of measurements included four X-ray images at angles \( \psi = 0; 26.6; 39.2 \) and 50.8\(^\circ\) gr, where \( \psi \) is the angle between the normal of the reflecting plane (hkl) and the normal of the irradiated surface of the sample. For control purposes, a thin copper foil was placed on the irradiated central part of the sample surface L (2-3) after each change \( \psi \) and the reflection from it was recorded (331). The radiation source (focus of the BSW33 Cu tube) and the detector were installed at an angle of 69\(^0\) to the sample plane to register the reflection (211) with the interplane distance \( d = 0.8242 \) A\(^0\) at an angle of 2\( \theta \) about 138.3540 gr. They remained stationary during the survey, as provided for in the operation of the diffractometer with the coordinate detector LCD. In order to reduce defocusing when the angle \( \psi \) changes, the survey was performed with a narrow slit (~0.1 mm), with a beam divergence of less than 0.30. All measurements of the Bregg’s angles \( \theta_{\psi} \) for subsequent calculations were performed along the line of the K\(_{a1}\)Cu doublet.
Figure 3. Loading unit installed in the goniometric prefix of the diffractometer.

The survey and measurements were made at two angles $\phi=0^\circ$ and $\phi=90^\circ$, where $\phi$ is the angle between the sample axis and the plane of the incident and diffracted rays perpendicular to the goniometer axis. In the first case ($\phi=0^\circ$), the grains of the polycrystalline sample participate in the diffraction, in which the tension creates normal stresses on the planes (211), and in the second ($\phi=90^\circ$) - the normal component should be absent.

In the tests carried out for the two specified thermal conditions, the measured stresses were 765 and 780MPa when taken at an angle of $\phi=0^\circ$ (i.e. along the tension axis, and were not detected in the transverse direction ($\phi=90^\circ$)). Despite the significant difference in the temperature intervals of cooling (from 600 and 900°C), these values were very close as well as the yield strength of the EP741 alloy at room temperature ($\sigma_{0.2}=850$MPa). This is explained by the fact that in both tests, the compensation of the free elongation of the sample $\Delta l_{free}$, which was constrained during subsequent cooling, achieved during heating, was carried out due to elastic tension $\Delta l_{elastic}$ and plastic deformation in the central zone of the sample L(2-3). At the same time, the plastic deformation continuously increased as the temperature decreased (according to the estimate, from 500 and 780°C with cooling from 600 and 900°C, respectively) and reached different values in the experiments. On the other hand, the elastic deformation, equal to $\sigma_{0.2}/E$ (T), changed very little. In this case, the stresses ($\sigma$) in the sample area L(2-3), being close to $\sigma_{0.2}$, varied in accordance with its temperature dependence.

3. Conclusion
A method for determining macrostresses in the semi-cycle of cooling tests for thermal fatigue and a device for its implementation is proposed.

The advantage of the method is that the measurements are carried out on a sample used in serial tests, and allow you to model and study the changes occurring in them.

It seems that it is advisable to determine the stresses repeatedly, at different stages during the thermal fatigue process.

4. References
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