The effect of asymmetry of the loading cycle on heat dissipation in metal structures

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Abstract. The paper is devoted to the experimental study of heat generation processes in various metallic materials under high-cycle loading with different values of asymmetry and amplitudes of cycles. Tests were performed on flat, smooth specimens subjected to cyclic stretching with increasing amplitude. Change in thermal radiation detected by an infrared detector, by the value of the thermal sensitivity of the device NETD was taken for the beginning of a metal sample self-heating. The stresses corresponding to the beginning of self-heating, are called critical. It has been established that Smith and Haigh diagrams of critical stresses of the onset of self-heating are similar to the same diagrams of ultimate fatigue stresses.

1. Introduction

It is known that during the destruction of a metal structure under mechanical loads, the accumulated energy is released and dissipates largely as heat [1, 2] – i.e. the material is self-heating. This phenomenon accompanies any type of fracture – transition to a plastic state, rupture upon reaching the strength limit, fatigue damage under low- and high-cycle loads. It is obvious that energy dissipation can be used to characterize the state of metal structures, to identify and assess the degree of damage.

To register the amount of dissipated energy infrared detectors (thermal imagers) having a temperature sensitivity of not more than 0.05 °K are used. The main feature of IR detectors is the measurement of infrared radiation, characterizing the intensity of energy dissipation, not in a single point (as in pyrometers or thermocouples), but over a certain field of points. Such a field includes both a damaged area (apex of a visible or hidden crack) and intact areas. The thermal radiation gradient between the points of the damaged and intact areas gives information about the intensity of the development of destruction [3], and, therefore, indirectly allows us to make a prediction about the durability of the structure.

Assessment of structures durability is an important task in the operation of facilities. To identify damage that reduces durability, various methods of non-destructive testing are used during periodic inspections (acoustic emission, ultrasound, etc.) or strain gauge and vibration diagnostics with constant monitoring [4].

IR thermography is one of the relatively new methods of non-destructive testing. The advantages of IR thermography are the possibility of remote detection of damage, the minimum amount of preparation for measurements (sometimes measurements can be carried out without any preparation), obtaining results directly at the time of measurement, and ease of use.
Known successful application of the method of IR thermography to assess the fatigue life of bridges [3, 5, 6]. Used in the more general thermoelastic stress analysis (TSA) [7], this approach is referred to as self-reference lock-in IR thermography.

Many parameters have a significant effect on fatigue life – a complex (multiaxial) stress state, random stresses (for example, residual assembly from welding or caused by surface defects) [7, 8], asymmetry of the loading cycle. To use these parameters in the TSA method, it is necessary to conduct a special experimental study of this effect using IR thermography. In particular, residual stresses were studied by IR thermography in [10].

This article shows some results of experimental studies of the effect of the asymmetry of the loading cycle on the intensity of heat release in various materials under high-cycle loading.

2. Experimental

The development of fatigue damage in metals is known to be accompanied by the dissipation of the mechanical energy of deformation in the form of heat. The phenomenon of metal self-heating under cyclic loads, accompanied by an increase in the intensity of infrared radiation, is observed where the total stresses in the material exceed the critical ones, i.e. \( \sigma > \sigma_c \). By saying critical stress, we denote the minimum value of the maximum stress in a cycle at intense heat dissipation, leading to an increase in material temperature by a value of \( \Delta T \), begins. The value of \( \Delta T \) is the sensitivity of the device NETD \( \Delta T_{\text{NETD}} = 0.05 ^\circ K \).

At low cyclic stresses, the material of metal structures elements, even in dangerous places, is deformed almost elastically and there is no significant increase in heat dissipation during an oscillation cycle. The amount of heat released is small and is spent on heat exchange with neighboring slightly loaded sections, on convective heat exchange of the oscillating metal construction element with the environment and on local material self-heating. At higher stress levels, as a result of structural heterogeneity of the material, local microplastic deformations occur in locally stressed zones [5], which leads to a significant increase in heat release.

The resistance of many materials to fatigue failure depends on the asymmetry of the loading cycle. Therefore, in order to reliably estimate the fatigue strength of materials operating under asymmetric loading cycles, stress limit diagrams or lines of equal durability are constructed in coordinates \( \sigma_m / \sigma_{\text{min}} \) (Smith diagram) or in coordinates \( \sigma_m ~ \sigma_c \) (Haigh diagram). Here, \( \sigma_m, \sigma_{\text{max}}, \sigma_{\text{min}}, \) and \( \sigma_c \) are the mean, maximum, minimum, and amplitude values of the stresses of a specimen loading cycle, respectively. We shall note the great complexity of constructing these diagrams. For example, in order to construct these diagrams for a single material for different durabilities, it is necessary to test 7-10 batches of samples, approximately 20 samples in a batch until destruction at different asymmetry coefficients, then construct Weller’s curves and build Smith or Haigh diagrams afterwards.

Each point on the limiting envelope of these diagrams corresponds to the fatigue limit for the selected durability in the case of loading a sample with a loading cycle, the parameters of which correspond to the coordinates of the point characterizing this cycle: \( \sigma_m ~ \sigma_{\text{max}} / \sigma_{\text{min}} \) or \( \sigma_m, \sigma_c \). Since in this paper the fatigue process is associated with the critical stress of the beginning of self-heating under cyclic loading, the impact of the loading cycle asymmetry on the magnitude of such a critical stress was investigated.

Heat release, or more precisely, the intensity of the infrared radiation flux off the surfaces of test specimens from various alloys, was measured using thermograms obtained with a thermal imager, which has a temperature sensitivity of at least 0.05 ° C.

Samples made of steels 08X18H10T (chemical composition \( \text{C} \leq 0.08 \%, \text{Si} \leq 0.8 \%, \text{Mn} \leq 2 \%, \text{Cr} \leq 17-19 \%, \text{Ni} \leq 9-11 \%, \text{Ti} \leq 0.7 \%, \text{S} \leq 0.02 \%, \text{P} \leq 0.035 \%, \text{Cu} \leq 0.3 \%, \) the basic element is – Fe) and 30HGSAT (\( \text{C} \leq 0.28 – 0.34 \%, \text{Si} \leq 0.9 – 1.2 \%, \text{Mn} \leq 0.8 – 1.1 \%, \text{Ni} \leq 0.3 \%, \text{S} \leq 0.025 \%, \text{P} \leq 0.025 \%, \text{Cr} \leq 0.8 – 1.1 \%, \text{Cu} \leq 0.3 \%, \text{Fe} \sim 96 \%), as well as alloy BT-20 (\( \text{Fe} \leq 0.3, \text{C} \leq 0.1, \text{Si} \leq 0.15 \%, \text{Mo} \leq 0.5 – 2 \%, \text{V} \leq 0.8 – 2.5 \%, \text{N} \leq 0.05 \%, \text{Ti} \leq 84.94 – 91.7 \%, \text{Al} \leq 5.5 – 7 \%, \text{Zr} \leq 1.5 – 2.5 \%, \text{O} \leq 0.15 \%, \text{H} \leq 0.012 \%) were tested. A number of samples were made of 30HGSA steel with heat treatment corresponding to \( \sigma_{\text{ult}} = 635 \text{ MPa}, \sigma_{\text{ult}} = 837 \text{ MPa}, \) and \( \sigma_{\text{ult}} = 1470 \text{ MPa} \), where \( \sigma_{\text{ult}} \) is the ultimate strength of the material. The samples were flat with thickness \( \delta = 5 \text{ mm} \) (Fig. 1).
The test method was as follows. To improve emissivity, the working part of each sample was covered with matte paint. For fatigue testing, the specimen was fixed in a machine clamp. After that, the specified average stress $\sigma_m$ was created in the sample and the sample was subjected to cyclic loading, at which the amplitude component of the cycle – stress $\sigma_a$ – was stepwise increased. At each stage of loading, the sample was held for 10–20 seconds, during which the temperature at the stage stabilized.

The amplitude of the cycle was raised until at some stage of loading the self-heating in the working zone of the sample occurred. At the time of the start of self-heating, the stress was noted, which was taken as the critical $\sigma_{cr}$. Then another medium stress was created in the sample and the test cycle was repeated.

![Fig. 1. Samples for testing](image)

3. Results and discussion

The test results are shown in Fig. 2-4 in the coordinates $\sigma_m \sim \sigma_{max} (\sigma_{min})$, taken in the construction of the Smith’s diagram of the ultimate stress, and in the coordinates $\sigma_m \sim \sigma_a$, taken in the construction of the Haigh’s diagram. Here, the experimental points correspond to the parameters of the loading cycle, at which self-heating of some point of the working part of the sample begins, i.e. these lines of self-heating start correspond to lines of equal temperature rise on $\Delta T_{NETD}$.

![Fig. 2. Smith (a) and Haigh (b) diagrams of the critical stresses $\sigma_{cr}$ of the beginning of self-heating for steel 08X18H10T](image)
Fig. 3. Smith's diagram of critical stresses $\sigma_{cr}$ of the beginning of self-heating for steel 30HGSA with “+” $\sigma_{ult} = 635$ MPa, “•” $\sigma_{ult} = 837$ MPa, “o” $\sigma_{ult} = 1470$ MPa.

Fig. 4. Smith (a) and Haigh (b) diagrams of the critical stresses $\sigma_{cr}$ of the beginning of self-heating for alloy BT-20

Points “o” correspond to the experimental parameters of the loading cycle A, B, C shown on the Weller curves (Fig. 5).

Fig. 5 shows Weller’s fatigue curves for samples of the BT-20 alloy, obtained experimentally at different cycle asymmetry coefficients using the Weller method. Samples tested for fatigue were fully consistent with samples tested for self-heating. Using these fatigue curves, you can determine the number of cycles to failure, corresponding to the critical stress diagrams $\sigma_{cr}$ shown in Fig. 4. For example, the parameters of the loading cycle of the envelope of the critical stresses for points $A_1$, $A'_1$; $B_1$, $B'_1$; $C_1$, $C'_1$ (Fig. 4, a) and similar points $A_2$, $B_2$, $C_2$ (Fig. 4, b) correspond to points A, B, C on the
fatigue curves shown in Fig. 5. It can be seen that points A, B, C on the fatigue curves correspond practically to the same durability \( N_k \approx 2.65 \cdot 10^6 \) cycles.

**Fig. 5.** Weller curves for samples made of alloy BT-20; points on curves A, B, C correspond to points \( A_1, A_1' \); \( B_1, B_1' \); \( C_1, C_1' \) (fig. 4, a) and points \( A_2, B_2, C_2 \) (fig. 4, b)

Thus, the critical stress diagrams \( \sigma_{cr} \) shown in Fig. 4 are lines of equal rise in self-heating temperature or lines of equal durability \( N_k \), which for material BT-20 corresponds to \( N_k = 2.65 \cdot 10^6 \) cycles.

### 4. Conclusion

1. Using structural steels samples under a uniaxial stress state and asymmetric loading cycles, the heat release in the sample material with a stepwise increase in the operating time was investigated.
2. It has been stated that each material for any given loading cycle and selected type of deformation has its own critical stress. In the places of the sample, where the stresses are greater than or equal to the critical, heat dissipation is observed, leading to the self-heating of these sites.
3. For each sample, tested without damaging it, the diagrams of critical stresses of the beginning of self-heating are constructed in coordinates \( \sigma_m \sim \sigma_i \) (Haigh diagram), and \( \sigma_m \sim \sigma_{\text{max}} / \sigma_{\text{min}} \) (Smith diagram).
4. The fatigue tests carried out for the control samples of the BT-20 alloy before failure showed that the points of these diagrams in the coordinates of Haigh and Smith correspond to stresses equal to the values of the critical stresses \( \sigma_{cr} \) of the beginning of self-heating. Thus these points fit well on a line that has the same self-heating temperature or a constant critical stress \( \sigma_{cr} \) onset of self-heating, or the same durability of these samples, under fatigue loading with their cycle, the parameters of which correspond to this accepted critical stress \( \sigma_{cr} \). It is logical to assume that the same pattern will take place in other materials.

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### 5. References

[1] Naderi M, Amiri M and Khonsari M M 2010 On the thermodynamic entropy of fatigue fracture *Proc. R. Soc. A* **466** 423–38

[2] Fedorova A Yu, Bannikov M V and Plekhov O A 2012 *Frattura ed Integrità Strutturale* **21** 46-53

[3] Sakagami T, Izumi Y and Kubo S 2010 Application of infrared thermography to structural integrity evaluation of steel bridges *Journal of Modern Optics* **57** 1738–46
[4] Yashnov A and Kuzmenkov P 2018 Innovative aspects in developing bridge monitoring systems 
*MATEC Web of Conferences* **216** (*Polytransport Systems – 2018*) 01009

[5] Sakagami T, Mizokami Y, Shiozawa D and Izumi Y 2017 TSA based evaluation of fatigue crack 
propagation in steel bridge member *Procedia Structural Integrity* **5** 1370–76

[6] Bremond P 2007 New developments in thermoelastic stress analysis by infrared thermography 
available online at: http://www.ndt.net/article/panndt2007/papers/138.pdf

[7] Marsavina L and Tomlinson R A 2014 *Frattura ed Integrità Strutturale* **27** 13–20

[8] Malgin M G, Kirian V I and Dvorecky V I 2012 Calculation of local stresses in welded joint zones 
of large-sized space structures *The Paton Welding Journal* **4** 2–5

[9] Wolchuk R 2007 Discussion of "Consistent approach to calculating stresses for fatigue design of 
welded rib-to-web connections in steel orthotropic bridge decks" by Robert J. Connor and John W. Fisher *Journal of bridge engineering* ASCE **6** 811–15

[10] Amjad K, Asquith D, Patterson E A, Sebastian C M and Wang W-C 2017 The interaction of 
fatigue cracks with a residual stress field using thermoelastic stress analysis and synchrotron 
X-ray diffraction experiments. *R. Soc. open sci.* **4**: 171100