THE USE OF PHOTOELASTIC COATINGS IN INVESTIGATIONS OF EARLY STAGES OF FATIGUE FAILURE

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Photoelastic coatings a few tens of microns thick have proved to be rather effective in investigations of grain deformation in metals [1-3]. Reliable numerical results can be obtained by this method for very complex distribution of grain deformation under various conditions of stressing [2, 3]. This requires a proper selection of the coating thickness of suitable resolving power and the application of measurement compensation methods with photographic recording of differences in optical patterns.

Here the method of photoelastic coating was used in the investigation of the early stages of fatigue failure of steel and grey iron specimens at nominal (averaged over the cross section) stresses above and below the limit of proportionality. Coatings up to 50 μ thick made it possible to obtain strain distribution patterns at the selected surface of the specimen and to determine local values of strain in regions of its concentration prior to the appearance of microcracks, as well as during their incipient and development stages. Considerably heavier coatings (of the order of 1 mm) used by other investigators [4, 5] are unsuitable for detecting the effects of strain accumulation and the formation of cracks in microregions.

1. Experimental Equipment and Technique

The equipment for cyclic stressing includes a steel frame 1 to which specimen 2 is glued by an epoxy resin and clamped by bolts (Fig. 1). The frame is held in the clamps of a pulsator and, when loaded (within its limits of proportionality), can strain the specimen well above the proportionality limit of the latter. This arrangement permits control of either the nominal stress ("soft" loading) or the nominal (averaged over the volume) strain ("rigid" loading). The nominal strain is controlled in the course of an experiment by the pulsator manometer, and the stress is measured by resistance strain gauges 3 glued to stem 4 of frame 1. Current from the strain gauges is fed to oscillograph 6 via the amplifier 5. For alternating load with the one-way acting pulsator, the specimens were attached to a prestressed frame which, during the

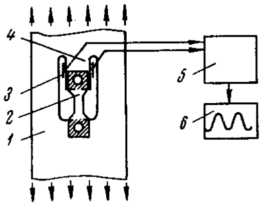

Fig. 1

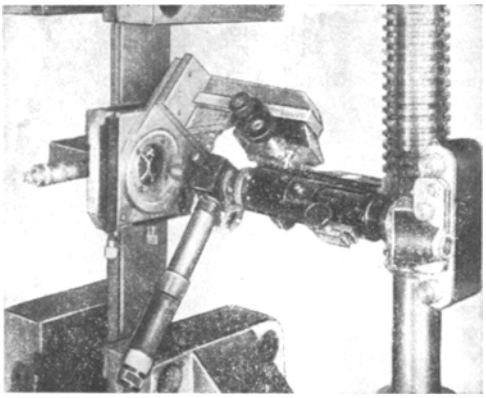

Fig. 2

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Fig. 3

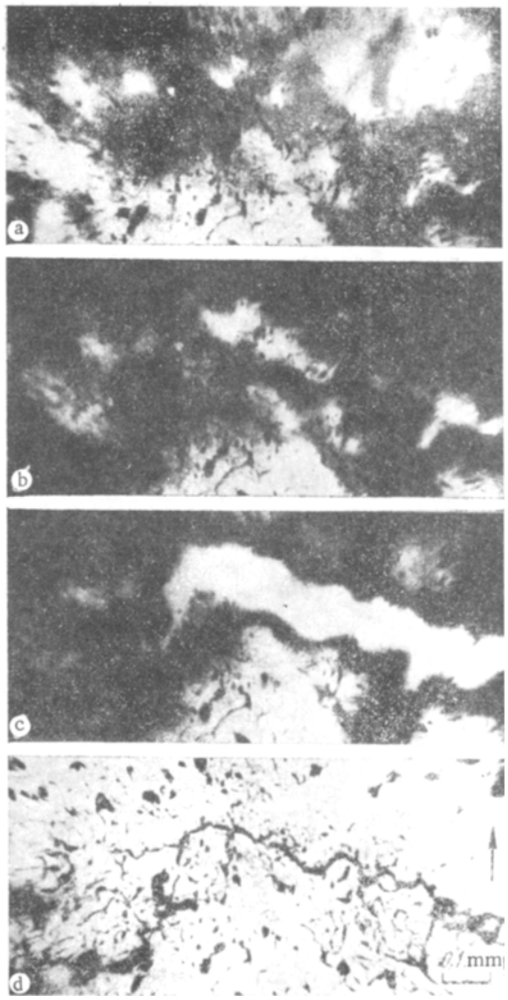

Fig. 4

hardening of glue, was maintained under constant stress. In this manner, an alternating loading is obtained by means of pulsating tension.

Patterns of interference lines in the coating, corresponding to $\varepsilon_1 - \varepsilon_2 = \text{const}$, were recorded by means of polarimetric equipment [2, 3] consisting of an MP-6 microscope with an immersion compensator and a photographic camera (Fig. 2). During a test the whole working part of the specimen was constantly scanned. Photographs were taken after 1, 10, 10^2, ..., and 10^6 stress cycles, or more frequently, whenever required. The pulsator was stopped at the instant of taking a photograph, and the nominal stress (for soft loading) was maintained at the level of the maximum stress of the cycle. In the case of rigid loading, the photographs were taken at fixed maximum nominal strain of the cycle.

Flat specimens of 2 × 3 mm cross section and 6-8 mm working length were used. Each specimen was given a 0.04-0.05-mm-thick coat of ED-6M material by the method described in [3]. The strength of this coating was, as a rule, considerably higher than that of the ED-6M material, as determined by its tests on standard test pieces (not as a coating on metal). Thus, in spite of its proportionality limit corresponding to the strain $\varepsilon_* = 2\%$ and an endurance limit $\sigma_{-1} = 2$ kg/mm^2 corresponding to the strain $\varepsilon_{-1} = 0.7\%$, it was possible to obtain with coatings of this material reliable measurements up to a strain of 4-6% without permanent deformations and cracks in the coating itself. Permanent deformations, measured on coatings separated from fractured specimens by etching were negligible.

2. Results of Experiments.

Tests on Grey Iron Specimens ($\sigma_b = 14.8$ kg/mm^2). The specimens were subjected to pulsating tension load with the minimum and maximum nominal stresses in a cycle ranging from $\sigma_{\min} \approx 0$ to $\sigma_{\max} =$

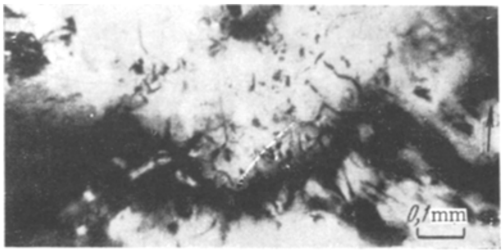

Fig. 5

5-9.5 kg/mm^2 for various specimens. A concentration of deformation on the surface of specimens was observed as early as after the first cycle. If the maximum nominal stress of a cycle did not exceed 6 kg/mm^2, the number of deformation regions in the working part of the specimen was small. The regions of concentration were generally located in the vicinity of graphite flakes. Further cyclic loading of specimens resulted in an increase of maximum deformation in the regions of concentration. This was accompanied by a simultaneous increase of the size of concentration regions and the appearance of new regions not previously noted. The strain field of a part of a specimen at the instant of maximum stress after the first (solid lines) and the 10^4-th (dashed lines) cycles are shown in Fig. 3a for $\sigma_{max} = 6$ kg/mm^2. Values of the difference of principal strains along the lines of $\varepsilon_1 - \varepsilon_2 =$ const are given in percent, and the arrow indicates the direction of tension. Some of the photographs used for plotting these lines are shown in Fig. 3b and c. The photograph in Fig. 3b was taken after the first cycle, and that shown in Fig. 3c — after the 10^4-th cycle. The difference of principal strains $\varepsilon_1 - \varepsilon_2 = 0.7\%$ at the specimen surface corresponds to the interference band on these photographs. We would point out that the band shown here was obtained under conditions of simultaneous transillumination of the coating and of the compensator [2, 3].

Failure of these specimens initiated by the gradual growth of one or more microcracks which frequently developed on the specimen surface where the initial concentration of deformations was comparatively small. The regions of concentration had, however, a definite effect on the direction and the rate of propagation of microcracks in the vicinity of these. The rate of propagation of microcracks was in many instances small, even under soft loading conditions. The life of specimens from the instance of appearance to a crack varied between a few tens to 3 × 10^4 stress cycles. The results of test on one of the specimens at $\sigma_{max} = 5.2$ kg/mm^2 are shown in Figs. 4 and 5. Since the location of incipient cracks was not known a priori, the whole surface of the specimen was succesively photographed. Photographs of bands (Fig. 4a-c) on the surface of the region where cracks did subsequently appear were chosen on completion of an experiment. The local strain of $\varepsilon_1 - \varepsilon_2 = 0.3\%$ at the surface corresponds to the interference bands on these photographs.

During the early stages of the loading process (approximately up to 10^4 cycles) the concentration at the location of the future crack (Figs. 4a, 4b) was relatively low. For comparison Fig. 5 shows the band pattern after the first loading cycle for another sector of the same sample where the concentration was highest. Here the interference band corresponds to a local surface strain of $\varepsilon_1 - \varepsilon_2 = 0.45\%$.

After 6 × 10^4 stress cycles the concentration at the spot of subsequent appearance of a crack was commensurate with that in other regions (Fig. 4c). After 7 × 10^4 cycles, closely spaced microcracks appeared in the specimen. The length of these cracks increased under further loading.

On completion of 8 × 10^4 cycles, this specimen was subjected to rigid loading, during which the nominal strain reached at that instant was maintained constant. The load acting on the specimen decreased with the increase of the number of cycles. This test approximates the conditions of stressing of a microvolume containing cracks bordering on a mass so far free of cracks. The developed (after 9 × 10^4 cycles) crack, shown in Fig. 4d, was photographed prior to the failure of the sample stripped of its coating.

The development of an individual crack under soft stressing ($\sigma_{max} = 5.5$ kg/mm^2) in another grey iron specimen is shown in Fig. 6a-c which shows characteristic fields of strain for a part of the working surface of the specimen after 3.53 × 10^4 (a), 3.86 × 10^4 (b), and 4.66 × 10^4 (c) stress cycles. These fields were obtained from phototographs of interference bands taken at various compensator settings [2, 3]. The specimen edge is shown here by a solid line, the crack by a heavy line, and the arrow indicates the direction of tension. During the initial stage of stressing, the crack tended to propagate mainly to the left. After

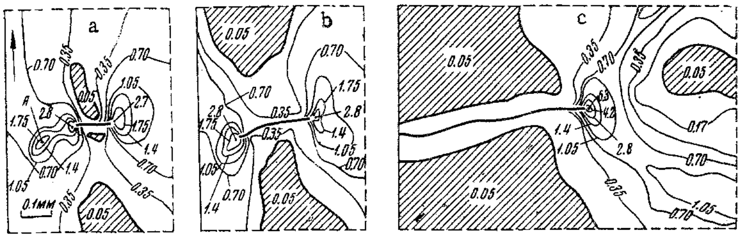

Fig. 6

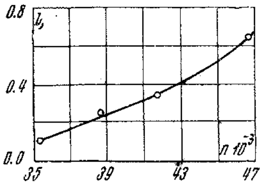

Fig. 7

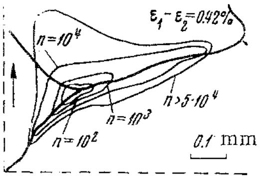

Fig. 8

reaching the edge of the specimen, it began to extend in the opposite direction. This pattern of crack propagation is probably related to the presence of a region of strain concentration near its left end (point A in Fig. 6a). The length l of the crack was continuously and uniformly increasing with the number of stress cycles (Fig. 7) until just before the failure of the sample (5.02×10^4 cycles), when its rate of propagation had sharply increased.

A simultaneous increase of the length of the crack and of strain in the vicinity of its ends was observed during the cyclic stressing process. Up to 3.8×10^4 cycles, the variation of strain at the crack ends was small (the strain field only "shifted" together with the crack end). Subsequently, particularly during the period of rapid development of the right end of the crack, a considerable increase of strain was observed here. The ratio of the maximum differences of principal strains at the end of the crack after 3.53×10^4 and 4.66×10^4 stress cycles was 2.3. This increase of strain cannot be explained by the decrease of the effective cross section of the specimen owing to the increased crack length. In several cases in which the length of cracks in the samples was approximately the same, the pattern of strain distribution and their maximum values near the crack ends were similar.

A considerable number of fairly closely spaced concentration regions were observed on the surface of the specimen at maximum stress of a cycle $\sigma_{\max} \gg 6$ kg/mm^2. Further cyclic stressing resulted in an increase of regions of considerable strain concentrations which gradually merged and spread over most of the specimen width. There were no visible cracks at this stage. Later, a crack began to develop along the line connecting two most strained regions. The rate of propagation of this crack was high, and the latter spread over the whole width of the specimen in the course of a single stress cycle.

Spread of Deformation in EZA Steel Specimens (limits of proportionality $\sigma_* = 35$ kg/mm^2, $\sigma_b = 53$ kg/mm^2, and endurance limit $\sigma_{-1} = 25.5$ kg/mm^2). Steel specimens were also tested under conditions of pulsating tensile load and nominal stresses $\sigma_{\min} \approx 0$ and $\sigma_{\max} = 20$–35 kg/mm^2. Strain concentration was observed in microregions as early as during the first cycle, which corresponds to a static loading (see also [2, 3]). The concentration zones were found, as a rule, in the neighborhood of convergence of three grain boundaries, mainly along boundaries at an angle of 45° to the direction of tension. Depending on the maximum cycle stress, the maximum strain in a cycle varied between 0.4 and 3%.

Two patterns of strain variation over the specimen surface were observed during cyclic stressing. The first appeared during the initial stage of stressing (up to $n = 10^4$–10^5 stress cycles, depending on $\sigma_{\max}$) with the maximum cycle stress below 30 kg/mm^2, when a simultaneous increase of strain in the concentration regions and of the size of these regions took place with increasing number of cycles. Lines of $\varepsilon_1 - \varepsilon_2 = \text{const}$ along which the difference of the principal strains is equal 0.42% after 10^2, 10^3, 10^4, and 5×10^4 stress cycles ($\sigma_{\max} = 23.4$ kg/mm^2, and grain boundaries are shown by heavy lines). Within regions bounded by these lines $\varepsilon_1 - \varepsilon_2 > 0.42\%$. It will be seen that up to 10^2 cycles the size of the region of $\varepsilon_1 - \varepsilon_2 \gg 0.42\%$ increases only slightly, after which it begins to grow at a considerably faster rate. The pattern becomes stabilized after 5×10^4 cycles, and further stressing up to 10^6 cycles did not alter the strain configuration or lead to the appearance of cracks.

In certain cases regions of strain concentration were also observed inside grain boundaries. The variation of the size of these regions with the number of stress cycles was similar to that described above.

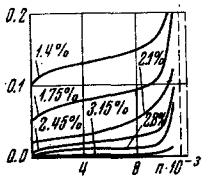

Fig. 9

In addition to the increase of the size of strain concentration regions produced by the first stress cycle, the appearance of new regions was observed on a few individual specimens after up to 10^5 stress cycles. These regions, similarly to the original ones, usually appeared at grain boundaries but much less frequently inside a grain, and were at an angle of 45° to the direction of tension. The variation of the configuration and size of the new zones were similar to those of regions developed in the initial stages of stressing. The size of these regions became stabilized after 2×10^4–10^5 cycles from the instant of their appearance (depending on $\sigma_{\max}$).

When the maximum cycle stress exceeded 30 kg/mm^2, the pattern of strain variation on the surface of a specimen differed from that described previously. The maximum strain in concentration regions was continuously increasing with increasing number of stress cycles. At the same time deformation was spreading to adjacent regions, covering an ever increasing part of the specimen surface. This spreading was particularly pronounced in the beginning of the test and immediately before failure. The growth of the total area of strain exceeding a certain value (at $\sigma_{\max} = 30$ kg/mm^2) is shown in Fig. 9 for one of the specimens. The ratio of the area bounded by lines $\varepsilon_1 - \varepsilon_2 = \text{const}$ to that of the total surface of the working part of the specimen is shown here along the vertical axis, and the dashed line indicates the number of cycles resulting in specimen failure. Under soft stressing conditions such specimens failed during a single cycle.

These results indicate the feasibility of investigating the early stages of fatigue failure of metal by the method of thin photoelastic coatings.

LITERATURE CITED

1. B. A. Kuznetsov, "On the initial stages of plastic deformation of polycrystals," Dokl. AN SSSR, 159, No. 1, 1964.
2. A. Ya. Aleksandrov, L. A. Krasnov, and V. A. Kushnerov, "Investigation of strain in microregions of polycrystals by means of photoelastic coatings," PMTF, 8, No. 3, 1967.
3. A. Ya. Aleksandrov, L. A. Krasnov, and V. A. Kushnerov, "The method of photoelastic coatings in the investigation of strain in metal grains," Tr. Novosib. Inst. Inzh. Zh.-D. Transp., 62, 1967.
4. P. T. Bogdyl', V. V. Larionov, and N. I. Prigorovskii, "A method for the investigation of elastic-plastic strain under repeated alternating loads," Zavodsk. Laboratoriya, 31, No. 9, 1965.
5. V. V. Larionov, "Kinetics of the stressed state and the failure in concentration regions under cyclic stressing," in: Resistance to Strain and Failure at Small Numbers of Stress Cycles [in Russian], Nauka, Moscow, 1967.