METHODS OF TESTING

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POSSIBILITIES OF FRACTOGRAPHY

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A brief characteristic of methods of observation, measurement, identification, and analysis of fractures is presented. Prospects of the use of the methods of fractography for solving problems of certification of materials, determining the structural mechanisms of fracture, and controlling the quality of metals are discussed. The combination of a digital photographic camera with special software for processing images opens up wide possibilities in the field, which are not used in full yet.

The main purpose of structural materials is to resist residual strain and fracture. Man perceives over 90% of the information he needs by eyes. In this connection the understanding of fracture depends much on the possibility of seeing if not the process (which occurs at a high speed and inside the material) then at least the result, i.e., the fracture surface. Almost all knowledge on fracture has been received from observations of fractures.

In situ observations. Propagation of a crack was first observed under a microscope in situ by N. P. Shchapov (1930) who loaded a metallographic specimen “on the side.” In this way we can see over which of the components of the microstructure (or over boundaries of grains or phases) the crack propagates predominantly.

In brittle fracture the process of crack propagation both on the surface of a specimen and in its volume can be the same, which is proved by comparing fracture surfaces. In fatigue and creep, crack propagation can be observed in the microstructure of aluminum, titanium, and nickel alloys and in coatings deposited on them [1]. However, the surface of a ductile fracture has a zone of contraction and shear, where the process differs radically from that in the bulk.

When a foil was stretched in [2] under transmission electron microscope, the nucleation and growth of a crack was observed at a resolution of 1 – 10 nm. However, this process differs from that in a massive specimen. Even in a high-voltage (1 – 2 MV) microscope the thickness of the “transmitting” foil does not exceed 1 μm. As a rule, a crack in a metallic foil appears on the external surface and has no plastic zone (because the source of generation and accumulation of dislocations requires a much larger area than 1 μm). A plastic zone of a crack 3 μm long has been observed in a ceramic foil (MgO); the zone contained up to 20 dislocations but they had been generated by the surface of the foil [3].

Observations with atomic resolution are even more specific: “a small object is required for high magnifications.” “Absolutely brittle cleavage” (without plastic relaxation), which turned out to be reversible (the lattice progressively broke upon loading but recovered upon unloading), has been observed in a field-ion microscope, where a tungsten needle sharpened to about 10 nm was split by electrostatic field at a temperature of 4 K. Breakage of copper whiskers about 10 nm in diameter has been observed in a scanning tunnel microscope “from a side,” but the whiskers simply contracted “into a point.” Thus, having observed in situ “absolutely brittle” or “absolutely ductile” fracture of a crystal lattice we did not learn much about fracture of actual structures.

Means for observation of fractures. Fractography, i.e., observation, recording, measuring, and analysis of fracture surfaces, gives most data on fracture processes. Virtually any known means of microscopy and macro photography can be used for fractography. These means can be classified in the following ways:

(a) in accordance with the radiation used, i.e., light, electron, emission (atomic, x-ray, electron, light), or radiation-free (sensed by a rigid probe);
(b) in accordance with the method of sensing and detection of the image, i.e., integral (recording the entire field of vision simultaneously) and scanning (cross-line, line-by-line).

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(c) in accordance with the dimensionality, i.e., direct three-dimensional 3D-detection, synthesis of a 3D picture from several 2D pictures (stereophotogrammetry), indirect analysis of 3D-features from a 2D frame (“plane” photograph).

Sometime ago special microscopes have been produced for measuring the height of a texture (point-after-point, manually, with an error of 8–30%), i.e., interference, multibeam, phase-contrast, light section, scanning ones. Today a metallographic microscope makes it possible to detect and synthesize a three-dimensional picture layer-after-layer. A general tendency is to replace the variety of apparatuses by a universal microscope with a digital photographic camera, a personal computer, and powerful software for processing the images in order to solve diverse problems (including three-dimensional ones).

A photographic camera with a “notebook” (or a stationary analyzer with a mobile telephone) will be effective as portable devices (for stereomicroscopy of fractures of mountainous rocks and materials including diagnostics of rejects and review of emergencies).

The speed of digital analysis of video frames is also enough for continuous control of the state of the surface of a piece or a tool under conditions of production, for example, the macrodefects of a sheet moving at a speed of 22 m/2 for continuous control of the state of the surface of a piece or a tool under conditions of production, for example, the macrodefects of a sheet moving at a speed of 22 m/2 or of operating rolls.

**Resolution.** The possibilities of a method are characterized by:

- resolution $\delta x$ in the plane of the photograph;
- resolution $\delta z$ over the height of the texture;
- sizes of the sharply visible region over the height (resolution depth).

The least resolved part is specified by the mode of functioning of the devices for photography and detection. In a light microscope an object is differentiated from a point if its size exceeds the half length of a wave of visible light ($\lambda = 0.4 – 0.8 \mu m$). A frame shot by digital camera consists of individual points (pixels). At $N$ pixels in a line a square frame contains $N^2$ pixels. If $N = 2^{10} = 1024$, the frame contains $N^2 \approx 1$ Mpixel. High sharpness (definition) corresponds to $N^2 \approx 4$ Mpixel; very high sharpness corresponds to $N = 2^{12} = 4096$, i.e., $N = 16$ Mpixel. The conventional size of a viewed frame convenient for the eye $B \approx 10$ cm. In photography with magnification $M$ per one pixel of the matrix the design size of an element of an object $\Delta = B/(NM)$. Magnification is useful until $\Delta \geq \lambda/2$ or $M \leq 2B/(N\lambda) \approx 300/(N/1000)$.

Software for conversion to higher resolution will just “smear the image smoothly” for more convenient review without improving the sharpness. The resolution of “wet” photography is also no better than several Mpixels (here a film grain plays the role of a pixel). In addition, any measurement or preparation of a photograph for printing is begun with digital sensing with the same constraints.

In order to observe large fields we can glue many frames into a panorama (and automatically “stitch the edges,” removing the results of distortion of periphery by the objective and the differences in the brightness and color). Some information will be lost; the panorama preserves the same 1–4 Mpixel (depending on the quality of the monitor) of all the frames. However, this is enough at present; in contrast to astronomy a fractographic photograph has never detected an object invisible to the eye under a microscope.

In scanning electron microscopes the effective resolution “in the plane of the object” in operation in secondary electrons (with an energy about 100 eV) is limited by the definition of the primary beam, i.e., $\Delta \sim 5 – 50$ nm; however, in reflected electrons (about 30 keV) the diameter of the radiating spot $\Delta \approx 1 \mu m$ is determined by the depth of their penetration. This smears the fracture topography.

The size of a measurable object is also restricted by preliminary processing of the photograph [5]. The nonuniformity of the illumination over the field is removed by subtracting the background (in the form of a two-dimensional polynomial, a spline, or a Fourier series of $k$ low-frequency harmonics). Point “eruption” is removed by smoothing on a sliding square of $n^2$ pixels. The sought-for element will not be distorted if it is larger than $n\Delta$ and smaller than $N\Delta/(4k)$ (as a rule, $n \approx 3 – 4$ and $k \approx 3 – 4$).

**Three-dimensional photography.** A light microscope has a low resolution depth ($h \sim 2 \mu m$ at magnification $M \sim 500$). This is not an obstacle as such, i.e., if only a small part of a fracture can be seen sharply, it is possible to create a series of photographs by changing the viewing depth, “cut” only the sharp part from each photograph, and then glue the cuttings to a whole picture. In the Image Expert Pro3 the “cutting and gluing” are automated; at the output you obtain a map with topographic horizontals (or with “geographic coloring” or a “panorama with shadows”).

However, such layer-after-layer microscopy is possible only for “flat enough” topography. The greatest difference in the heights of the topography should be less than the sharpness distance $f$ from the front bevel of the lens to the object (for a specimen not to touch the lens barrel). The higher the magnification $M$, the less the value of $f$.

Interference light microscopes measure the topography with height resolution $\delta z \sim \lambda/10$ of the light wavelength ($\lambda \approx 0.6 \mu m$); for multibeam and phase contrast microscopes $\delta z \sim \lambda/100$. For them the permissible drop in the topographic heights within a frame $z \leq 10\Delta$, but fractures this smooth are encountered rarely.

In a long-focus binocular stereomicroscope (with great $f$ but magnification $M < 100$) the frames “for the left eye” differ from those “for the right eye” in the direction to the object by an angle $\alpha = 5 – 10^\circ$. The stereoscopic pair is transformed into a map of the texture by methods of classical stereophotogrammetry. If the height of one point of the texture above another point is $z$, the mutual shift of their images on the “left” and “right” photographs (parallax) $x = z \tan \alpha \approx z \alpha$. Then at resolution $\delta x$ in the plane the minimum distin-