Experimental study of heat dissipation process into fatigue crack tip in titanium alloys.

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Abstract. Paper is devoted to investigation of initiation and propagation of cracks in titanium alloys by infrared thermography study of heat generation under cyclic loading and fractography analyses of fracture surface. Two series of experiments on cylindrical specimens and flat specimens with preliminary grown fatigue crack are carried out. Spatial and time temperature evolution into crack tip is investigated, the shape and dissipative intensity at crack process zone are estimated. Based on a result of comparative analysis of the experimental data and the linear fracture mechanics equations it is shown that the spatial distribution and character of heat dissipation zone into the crack tip doesn't correspond to the conventional models. High-speed shooting (at a frequency of 1 kHz) allowed us to determine the intensity and shape of zone of energy dissipation caused by plastic deformation at the crack tip, as well as to compare the rate of energy dissipation for different stress levels. Fractured specimens were analyzed by interferometer microscope and SEM to verify the existing models of inelastic deformation at the crack tip and to improve methods of monitoring of damage accumulation during fatigue test.

Keywords fatigue, energy dissipation, thermo elasticity effect, infrared thermography, fractography

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1. Introduction

The heat Dissipation caused by the evolution of the structure of the material under cyclic deformation, is the subject of intense research over recent decades. At present it is known that under cyclic deformation processes of strain localization are accompanied by intense heat generation, which makes possible early detection by infrared thermography [1].

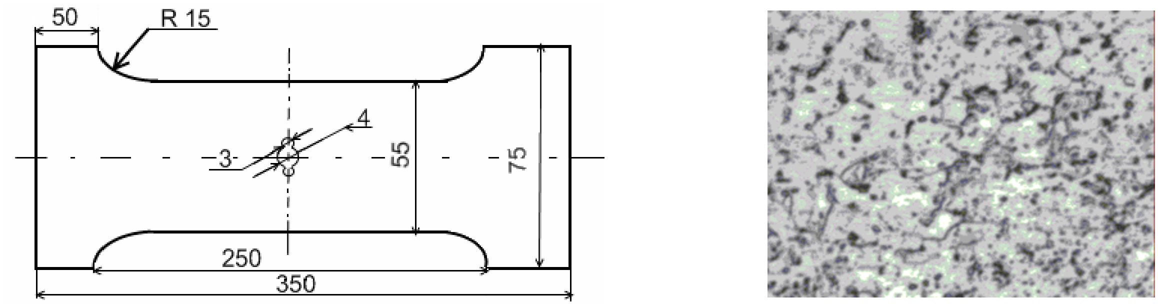
Due to its versatility, method of infrared thermography recently been actively used at carrying out mechanical tests as to obtain detailed information about the process of nucleation and propagation of fatigue cracks [2-3] and for studying laws of conversion and energy storage during deformation [4-5]. The possibilities of the method of infrared thermography allows real-time to explore the processes of change temperature caused by thermoelasticity and localization of deformation at the crack tip, as well as the effects of friction on the crack faces during its propagation.

This paper is devoted to researching thermoelastic and thermoplastic effects in the crack tip propagating under the cyclic tensile stress applied normal to the plane of the crack. Experimentally obtained cooling effects caused by the elastic deformation of the material at the crack tip, and investigate the features of the distribution of stresses at the crack tip. High-speed photography allowed us to determine the intensity and shape of the zone of energy dissipation caused by localized plastic deformation at the crack tip, and compares the rate of energy dissipation for different stress levels.

2. Experimental conditions and materials

Experimental study of temperature evolution at the fatigue crack tip was carried out on the plane specimens of titanium alloy Ti-4.2Al-1.6Mn with frequencies ranging from 1 to 20 Hz in low-cycle fatigue regime were investigated. Test samples were prepared from sheet with thickness 3 mm. Geometry of specimens shown in Figure 1. In order to study thermal effects at the crack tip, specimen was pre-weakened by holes (Fig. 1a).At the initial stage of the experiment with the increased load was created fatigue crack with size of about 10 mm. Initiation of the cracks was carried out at an average load of 215 MPa, load amplitude 238 MPa and loading frequency 20 Hz. Then load was decreased for slow down crack propagation rate and for detailed study of heat generation processes in the crack tip.

Mechanical testing were carried out at 100 KN servo-hydraulic machine Bi-00-100. Analysis of the results of quasi-static testing of investigated material determine following mechanical properties of the material: Young's modulus of 64 GPa $\sigma_{0.2}$ = 683 MPa $\sigma_{\text{в}}$ = 790 MPa.



a) b)

Fig. 1. Geometry a) and structure b) of the Ti4AlMn samples to study the thermal effects in the crack tip.

During investigation the process of thermoelasticity, samples was loaded in the elastic range at frequencies 0.5, 1, 5, 10, 20 Hz and different amplitudes ranging from 100 to 350 MPa with the coefficient of asymmetry of the cycle, R = 0. To determine the strain during the experiment used an axial extensometer - Bi-06-304 with an accuracy of ± 1,5 mm.

The temperature field study was carried out by infrared camera FLIR SC 5000. Recording of the temperature field was carried out at frequencies from 350 to 950 Hz and a minimum spatial resolution from $2 \cdot 10^{-4}$ m. For the calibration of camera used standard calibration table.

During the experiment grips and specimen was shielded from external heat sources by special screen. Surface of the specimen was polished in several stages by abrasive paper (final stage of polishing grit size does not exceed 3 μm); before start of the experiment, polished surface was covered by thin layer of amorphous carbon.

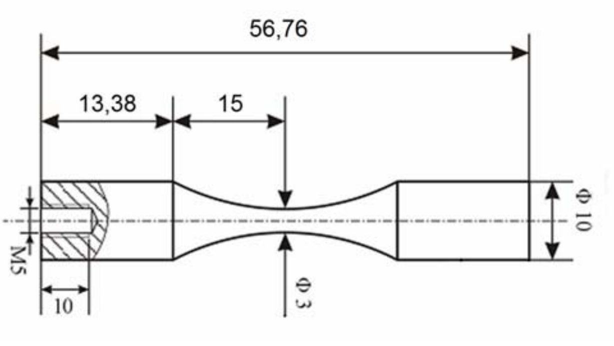


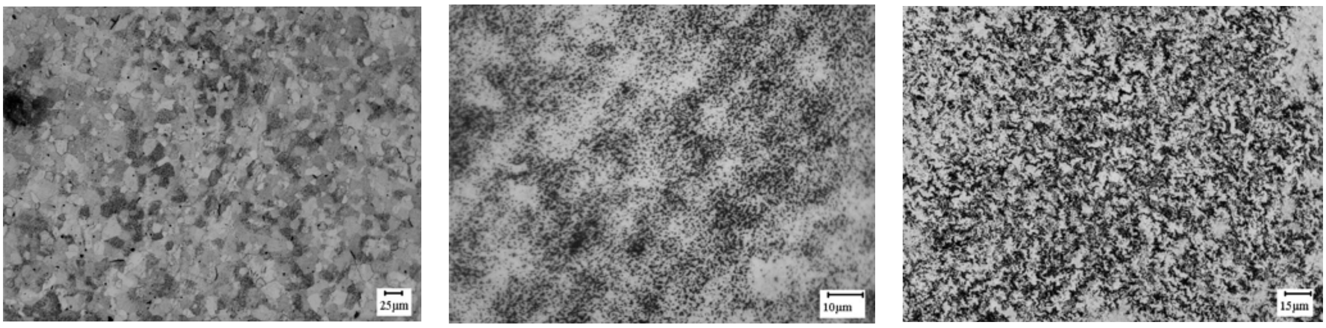
Fig.2 Typical geometry of cylindrical specimens

The second kind of experiments was carried out with cylindrical specimens (fig. 2) of pure titanium Grade 4 with different grain sizes (~25 μm and ~ 500 nm Fig. 3) to evaluate influence of grain size on fatigue strength and its dissipation properties. Structure was studied in optical microscope by chemical etching of prepared surface by sanding disc from 160 to 4000 grains per sq. cm. and diamond suspension from 3 to 1 microns sizes.

Table 1. Chemical compound of the etching:

HNO_3	2%,
HF	2%
H_2O	96%

After polishing materials was etching by compound with shown in table 1, time of etching – 10 seconds.



a) b) c)

Fig. 3.Structure of the Ti Grade 4 samples to study influence of grain size on fatigue strength and its dissipation properties a) initial stage with grain size ~25 µm b) Stage under Equichannel angular extrusion in condition 1 c) Stage under Equichannel angular extrusion in condition 2

High cycle testing was carried out on BOSE testing machine in laboratory of Bordeaux with frequencies 50 Hz and 10 Hz with symmetric conditions (R=-1). Test was started from stress 200 MPa. During fatigue processing, the temperature of specimen was measured by infrared camera CEDIP. When the temperature of specimen surface is reach stable value, test stopped and stress increased on 20 MPa until we get sharp rise in temperature which means reaching fatigue limit

3. Theoretical description of changes in temperature of the metal during cyclic deformation

Evolution of temperature during cyclic deformation $\sigma = \sigma_A + \Delta\sigma\sin(\omega t)$ under the assumption of homogeneity of its distribution, the absence of structural transitions and plastic deformation can be described by the Kelvin equation:

$$\mathrm{Log}\,T_t = -\frac{\beta(1-2\nu)\omega}{\rho c}\Delta\sigma\cos\omega t\,, \qquad (1)$$

where β - coefficient of thermal expansion, ρ - density, c – specific heat capacity, ν - Poisson's ratio, ω - the angular frequency of loading, $(.)_t$ - time derivative.

The solution of equation (1) has the form:

$$T = T_0 \exp[-\frac{\beta(1-2\nu)}{\rho c}\Delta\sigma\sin\omega t]\,, \qquad (2)$$

series expansion of (2) taking into account the smallness of the ratio, which stands in the exponent, gives the following relations for the first and second harmonic:

$$A_1 = T_0 \frac{\beta(1-2\nu)}{\rho c} \Delta\sigma, \qquad A_2 = \frac{T_0}{4}\left(\frac{\beta(1-2\nu)}{\rho c}\right)^2 \Delta\sigma^2, \tag{3}$$

Analysis of the relations (2), (3) leads to the conclusion that in the classical case amplitude of the first and second harmonics does not depend on frequency and are linear functions of stress amplitude and the square of the stress amplitude, respectively.

At the present time been suggested that the effect of thermoelasticity is strongly nonlinear [6]. Significant contribution to the temperature dependence of the time makes the process of changing the elastic properties of the material on temperature. Assuming the dependence of the elastic modules of the material on the temperature (λ_T, μ_T), the temperature change is described by the equation:

$$\begin{aligned} \operatorname{Log} T_t = &\left(-\frac{\beta(1-2\nu)}{\rho c} + \lambda_T \frac{\sigma_0}{(3\lambda+2\mu)^2 \rho c} + 2\mu_T \frac{\sigma_0 (1.5\lambda^2 + 2\lambda\mu + \mu^2)}{\mu^2 (3\lambda+2\mu)^2 \rho c}\right)\Delta\sigma\omega\cos\omega t + \\ &+\left(\frac{\lambda_T}{2(3\lambda+2\mu)^2 \rho c} + \mu_T \frac{(1.5\lambda^2 + 2\lambda\mu + \mu^2)}{\mu^2(3\lambda+2\mu)^2 \rho c}\right)\Delta\sigma^2 \omega \sin 2\omega t \end{aligned} \tag{4}$$

At the tip of fatigue crack occurs intensive energy dissipation due to the localization of plastic deformation. The characteristic size of the zone of energy dissipation in framework of linear fracture mechanics, determined by the value of stress intensity factor. The magnitude of the stress intensity factor taking into account geometry of the sample can be estimated using the expression:

$$K = \sigma\sqrt{\pi a}\, Sec\left(\frac{\pi a}{W}\right)^{1/2}, \tag{5}$$

where W – wide of specimen, a– half-length of crack.The radius of the zone of plastic deformation on the surface of the plate is:

$$r_p = k\frac{K^2}{\sigma_y^2}, \tag{6}$$

where k – coefficient depending on the type of stress state and accepted model of plastic deformation, σ_y – flow stress. The form of the zone of plastic deformation at the crack tip under quasi-static tension can be described by the relations:
taking into account Mises criterion

$$r_p(\theta) = \frac{1}{4\pi}\frac{K^2}{\sigma_y^2}\left(1 + \cos(\theta) + 3\sin^2(\theta)\right), \tag{7}$$

taking into account Tresca Saint Venant criterion

$$r_p(\theta) = \frac{1}{2\pi}\frac{K^2}{\sigma_y^2}\cos^2\left(\frac{\theta}{2}\right)\left(1 + \sin\left(\frac{\theta}{2}\right)\right)^2. \tag{8}$$

4. Experimental study changes in temperature during elastic deformation.

Analysis of thermal effects at the crack tip is complicated by the fact that during normal loading to the plane of the crack propagation, its trajectory is not always strictly linear. The appearance of an inflection point on the trajectory of crack leads to a significant heat release on its banks (Fig. 4).Apparently, the edges of the crack are shifted relative to each other and cause the appearance of zones of friction and/or plastic deformation, which corresponds to the hypothesis of crack closure, is used in some models of linear fracture mechanics.

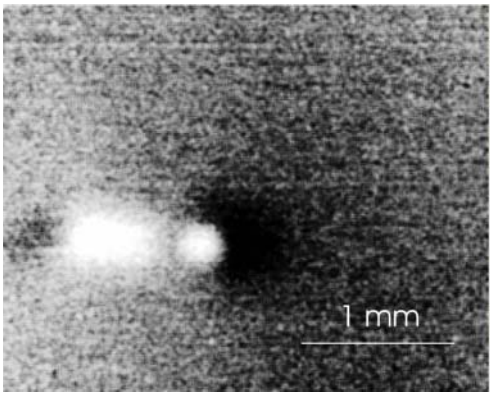


Fig. 4 The temperature distribution at the top and on the banks of the fatigue crack propagation under cyclic deformation

Figure 5 shows the change in the maximum temperature at the crack tip, stress and crack opening during loading with the stress amplitude 212 MPa, average stress 212 MPa and frequency of 5 Hz. Data from displacement sensor mounted on the crack faces, allows to suggest that the disclosure of the crack varies in phase with the applied stress.

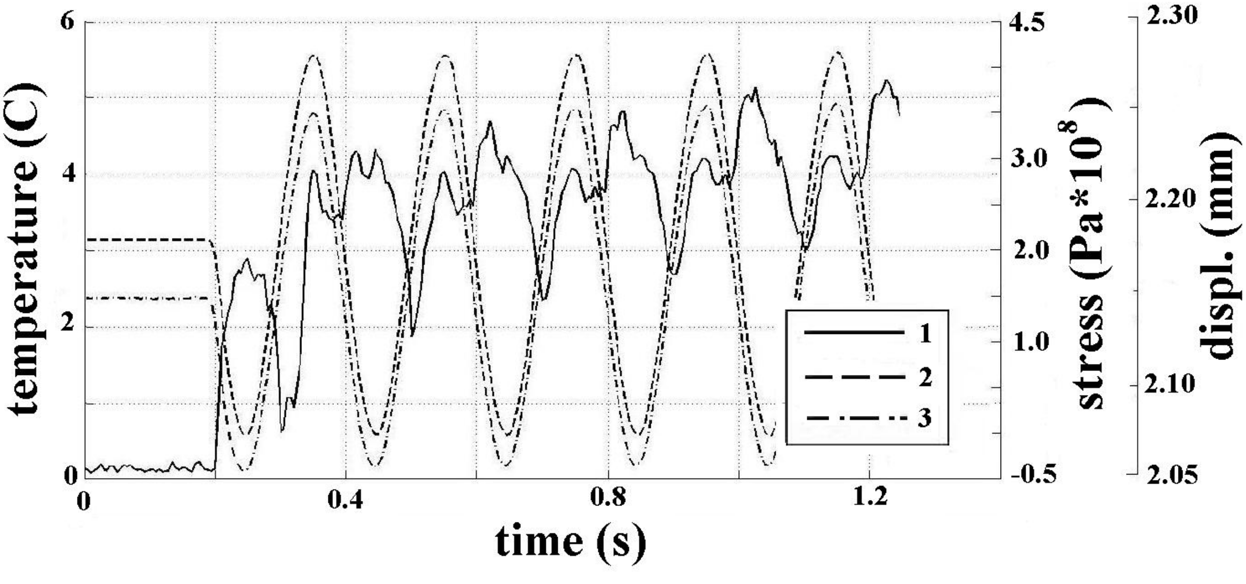


Fig.5. Changing the maximum temperature at the crack tip (1), stress (2), and the crack opening (3) in the process of cyclic loading with the amplitude of stress 212 MPa, average stress 212 MPa and frequency of 5 Hz.

Analysis of temperature data allows asserting, that the maximum of applied stress and the maximum of intensity of heat in the top of the fatigue crack does not match in time. At the beginning of the experiment the sample is loaded by middle stress and in a state of thermodynamic equilibrium. At each loading cycle is observed area of temperature drop caused by the thermoelastic effect, which goes to the site of temperature increase caused by the local transition through the proportional limit and the formation of zones of plastic deformation. During decrease stress in the crack tip heat generation are continues. The geometry of the zones of plastic deformation is shown in Figure 6. With decreasing stress at the crack tip heat increases and the temperature reaches its maximum at practically zero stress value. Then, at the beginning of the next cycle, the temperature drops due to thermoelastic effect and the process repeats.

The main goal in investigation of cylindrical specimens was to understand principles of crack initiation and propagation inside of specimen i.e. Fish eye. For achieve this goal specimens were tested in 2 regimes – multi-cycle fatigue with using infrared camera and giga-cycle fatigue. In giga-cycle fatigue regime rise of temperature was very high and not able to control without cooling – such way infrared camera was helpless in analyzing of structure parameters. During multi-cycle fatigue was determine fatigue strength of titanium specimens by Luong method [1]. For materials with usual structure it is work well, but for nano-grain structures it is not so accurate, because damage accumulated during the formation of such a structure start to heat much earlier than usual structure, but we still can to evaluate fatigue strength limit on sharp rise temperature point (fig. 6)

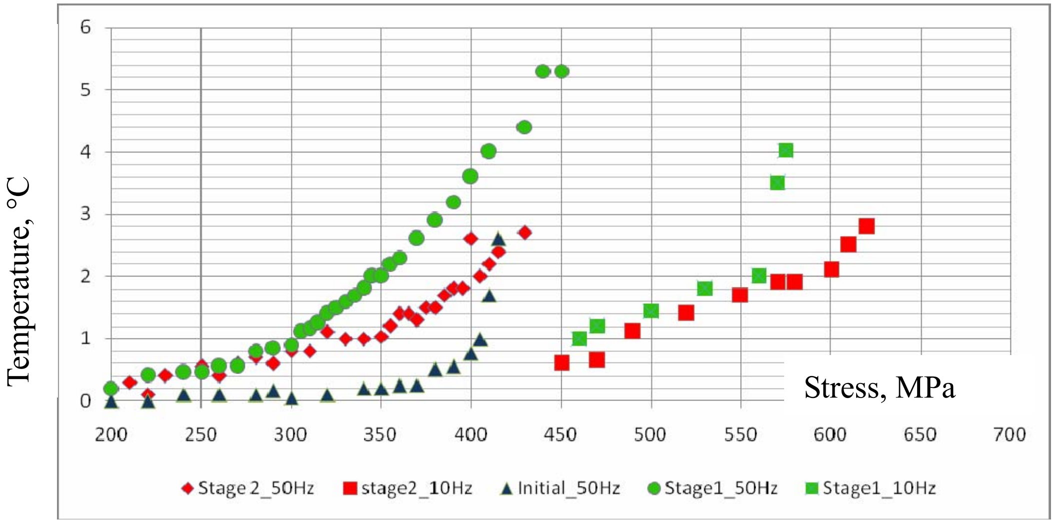


Fig6. The dependence of the surface temperature of the sample from the applied stress

Summarizing results of high cycling test and infrared camera, using Resitano-Luong technic, we can conclude that fatigue limit of Ti Grade 4 in initial stage is approximately 375 Mpa, in “Stage 1” 575 MPa, in “Stage 2” 600 MPa.

Infrared thermography methodic can high accuracy visualize zone of intense energy dissipation in the tip of fatigue crack (Fig. 7). The distribution of temperature in the crack tip during deformation may differ from the form of zones of plastic deformation due to the processes of heat conduction, so to analyze the geometry of the intense heat caused by plastic deformation, it is logical to use only the first cycle of deformation. Figure 7 shows a comparison of the observed shape of zones of intense energy dissipation in the first cycle of deformation and classical solutions of (3.4) to form zones of plastic deformation in the crack tip (in the calculations we used the following data: half crack length 4 mm, the applied stress 300 MPa). Analysis of the results suggests only a qualitative agreement forms zones of plastic deformation in the tip of fatigue crack propagation to models Mises and Tresca-Saint Venant.

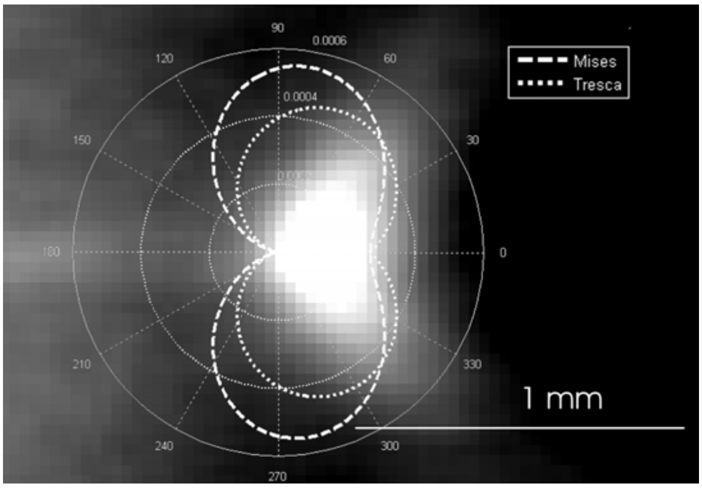


Fig.7. The form of zones of intense energy dissipation in the crack tip on the first cycle of deformation and plastic deformation zone, built on the criteria of von Mises and Tresca-Saint Venant.

5. Fractography analysis of fractured specimens.

Fractured specimens were investigated by optical and scanning electronic microscopes for qualitative analysis of fracture surface. Specimens with inside and surface crack initiation were observed. For quantitative analysis was used interferometer profiler New View 5010 which can get 3D image of investigated surface with digital data. Relief of fractured surface close to crack initiation and its propagation was analyzed.

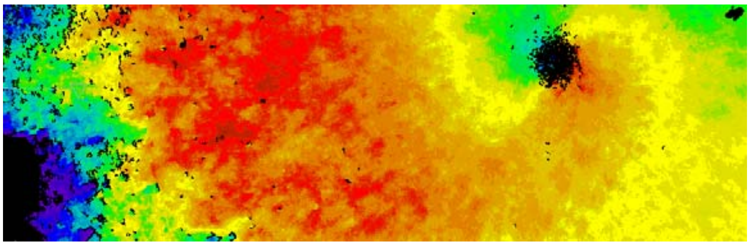


Fig 8. Typical relief of fractured specimen with inside crack initiation obtained on interferometer profiler New View.

In the study, one-dimensional image of the of the relief in certain selected sections, were analyzed by the method of Hurst in terms of the Hurst exponent, measured by the correlation function:

$$K(r) = \left\langle \underset{\{x,x+r\}}{Max}(z(x)) - \underset{\{x,x+r\}}{Min}(z(x)) \right\rangle_x \propto r^H \quad , \tag{9}$$

where z (x) - the height of the relief, depending on the coordinates, the angle brackets denote averaging over x, H - Hurst exponent.

In terms of Hurst exponent fractured relief had 2 zones with significant difference of H. First zone has circle geometry and its position around crack initiation with diameter ~ 300 μm. We assume that inside this zone was defect accumulation during fatigue loading. When this zone reach 300 μm diameter crack became instability and start propagate and we can see it on increasing of H. Second zone size reach cross section of specimen.

6 Summary.

Relations are obtained which describe change in temperature at the sample surface and the tip of fatigue crack during a uniaxial cyclic deformation taking into account the linear and nonlinear thermoelastic effects. Shown that the process of heat generation is essentially nonlinear. Using of infrared thermography methodic can effectively investigate the processes associated with both the localization of plastic deformation in the crack tip and the friction on its banks. At this stage, studies have shown experimentally that the zone of plastic deformation does not coincide with the predictions of the linear fracture mechanics, and the maximum heat is reached on the descending branch of the loading. Fracture surface has 2 zones with significant difference of Hurst exponent which correspond damage accumulation and crack propagation.

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