Method and results of reconstruction of the surface relief evolving under the action of laser radiation

D.V. Abramov, S.M. Arakelyan, I.I. Klimovsky,[1] A.O. Kucherik, and V.G. Prokoshev

[1] Thermal Physics Institute of Extremal States,
Scientific Association for High Temperatures, Russian Academy of Sciences, Moscow
Vladimir State University, Vladimir

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This paper describes the results of the investigation of the laser radiation interaction with metal surface. The investigations were performed of the effect of the pulse-periodic laser radiation on the material surface. Laser diagnostics of the interaction area was realized using a laser monitor (projection microscope). The method of reconstruction of three-dimensional relief was developed and realized based on the two-dimensional surface image by use of the dependence of pixel brightness on the tilt angle of the surface microplates. The correlation coefficients of the reconstructed reliefs were determined.

Introduction

The presently known methods of reconstruction of three-dimensional surface relief using its two-dimensional surface images (see, for example, Refs. 1 and 2) are based on the computer synthesis of the unknown relief from several surface images illuminated uniformly by a remote local (point) light source.

Laser monitors (projection microscopes[3]) theoretically make it possible to reconstruct the relief of the observed surface using a single two-dimensional image. In this case, for quantitatively reconstructing the relief, knowledge is needed of time averaged space-angular laser radiation characteristics like the angular directivity of the surface reflection being studied, and the space-angular distribution of the amplification factor in the laser active medium. However, the qualitative reconstruction of the surface relief under condition of independence of the reflection directivity of the angle of laser radiation incidence on the surface can be realized based on the obvious dependence of the brightness of a surface image point on the tilt angle of a surface microplate, on which this point is located.

Experimental setup

In this study we used, as the pump, radiation of a YAG:Nd^{3+} laser at $\lambda = 1.06$ μm operated in the pulse-periodic regime (pulse duration $\tau = 1.5$–2.5 ms, pulse repetition frequency $f = 150$ Hz), in this case the radiation power density on the sample surface (steel, lead, titanium, etc.) was up to 10^6 W/cm^2. As a monitor, a copper-vapor laser amplifier was used ($\lambda = 0.51$ μm, $\tau = 20$ ns, $f = 16$ kHz). Its radiation reflected from the action zone on the sample surface served a sounding beam. The resulting hydrodynamic regimes were recorded using a CCD-camera (with the response time on the order of 0.2 ms) and the corresponding projection optics (providing the spatial resolution of dynamic images no worse than 2 μm). Data were entered into a PC, which allowed us to process data and recognize the images both during the measurements and after them. Detailed description of the experimental setup can be found in Ref. 3.

Experimental results. Processing of optical images of the laser-affected area

Figure 1 shows the optical images of laser-affected area on the metal surface obtained using the above-mentioned experimental setup. During the action of a single laser pulse of the duration $\tau = 1.5$ ms the optical image character varied from regular at the beginning of action to random and wave structures. The first frame (Fig. 1*a*) corresponds to the moment of production of wave structures; in the second frame (Fig. 1*b*) we can see typical image of the surface at the moment of metal splashing under the action of the kickback vapor pressure at liquid boiling. The liquid splash is clearly defined in the form of turbulent stream of a ring shape, the third frame (Fig. 1*c*) can be interpreted as an expansion of the region of turbulent stream when the melt moves by inertia after completion of boiling and after disappearance of the kickback vapor pressure.

It is certainly interesting the possibility of identifying the images of the laser-affected area depending on the state of the substance surface.

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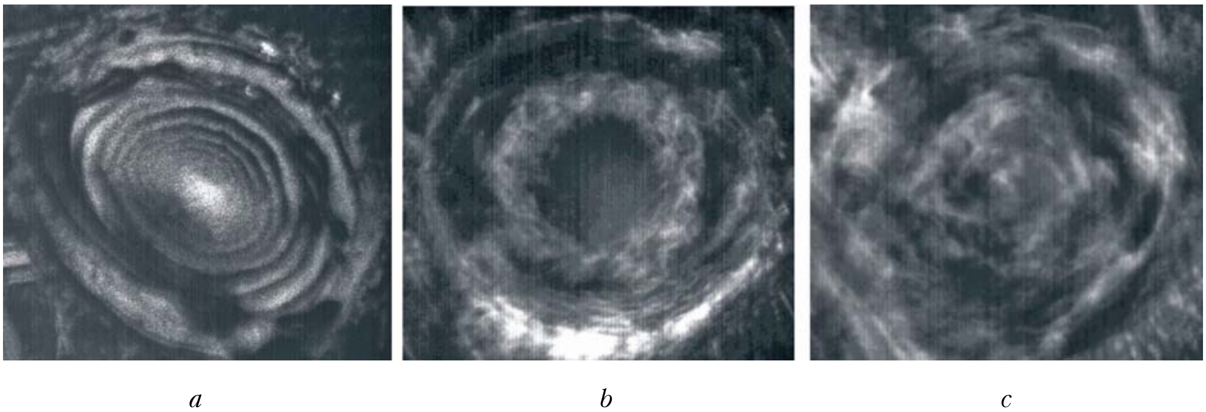

Fig. 1. Metal surface under the action of laser radiation: (*a*) waves on the surface; (*b*) turbulent splash of melt; (*c*) expansion of the turbulent zone.

Method of reconstruction of the surface profile evolving under the action of laser radiation

The method is based on the dependence of the brightness of a point in the surface image on the tilt angle of the microplate this point is located in. In this case, by the tilt angle we mean the angle between the normals to the surface and the microplate. We shall call it, in what follows, "tilt method." In the simplest case of laser radiation incidence on the surface (the angle of incidence $\beta \cong 0$) the main assumptions, used in this method, are formulated as follows:

– the reflectance (the reflection directivity) of the surface is constant everywhere over the area observed;

– the radiation source and the receiver are located on the same axis;

– the brightness of isolated image points corresponding to a microplate of the observed surface is a function of the tilt angle of this microplate. We consider that the characteristic size of a microplate is much larger than the radiation wavelength.

Based on the above assumptions, for the case of $\beta = 0$, we can formulate the following rules for reconstructing the surface relief.

1. The most bright points of the image correspond to the microplates on the surface that are oriented perpendicularly to the incident radiation and lying at the top or bottom level of the relief (these points are consistent with local/global maxima/minima of heights).

2. The less bright points correspond to the microplates located at a certain angle to the incident radiation, whose value, together with the reflection directivity, determines the difference in the brightness of an observed microplate and the microplate located perpendicular to the incident radiation.

3. Each separate microplate is characterized by positive or negative tilt angle α relative to the plane perpendicular to incident radiation.

4. The position of the microplate, corresponding to a point of maximum brightness on the image, is alternating, and its tilt angle α equals zero.

Now we consider the method of reconstruction of surface profile using as an example the one-dimensional surface (scanning line), whose image is characterized by a certain distribution of brightness along its length. Figure 2*a* shows this distribution in the form of the dependence $I(r)$.

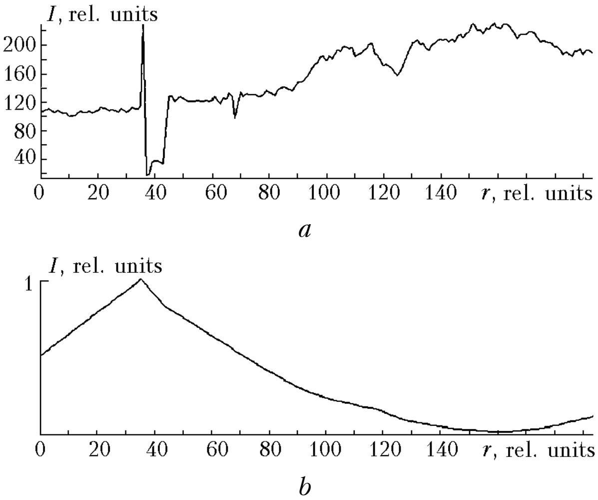

Fig. 2. Reconstruction of one-dimensional surface relief: the dependence of image brightness of one-dimensional surface on the distance r along a chosen line (*a*); the reconstructed relief of the one-dimensional surface (*b*).

The image point with the serial number 36, whose brightness is maximum $I = I_{\max}$, is determined as a point of the microplate, for which the tilt angle $\alpha = 0$. Besides it is assumed that the position of this microplate corresponds to the position of the upper point of the relief. Such an assumption determines uniquely the sign of the tilt angle α for $r < 36$ and $r > 36$.

In the calculations performed the experimental values of the dependence of brightness on the angle were used. For the purpose of a qualitative estimation of the influence of the reflection directivity on the relief characteristics and for simplifying the calculations we also used in this paper the model dependences of the tilt angle of a microplate on the brightness at the observation point I, corresponding to this microplate, which approximates the real reflection directivity.

Figure 2*b* shows the relief of one-dimensional surface, reconstructed from the brightness distribution presented in Fig. 1*a*, for the dependence of the angle α on the brightness I, determined by the ratio

$$\alpha = \arctan\frac{I_{\max} - I}{I_{\max}} / C,$$

where $I_{\max}$ is the maximum brightness of the image, C is the constant of approximation. It has been established that the height of raised portions and the depth of hollows of reconstructed profiles of the surface depend on the type of model dependence $\alpha = f(I)$. However, in a qualitative sense (according to the location of raised portions and hollows) the profiles are in a good agreement. In the above-mentioned case of one-dimensional surface the tilt angles of adjacent microplates are determined only by the orientation of these microplates with respect to the microplate with the angle $\alpha = 0$ appropriate to an image point with the peak brightness (in this case it is the point #36). In the case of two-dimensional (located in the plane) surface the orientation of a microplate depends on its position with respect to all the points of peak image brightness.

To determine the tilt angle of a microplate, which determines its brightness, on the two-dimensional surface image, it is necessary to take into account the orientation of the microplate along every radial directions passing through its center. At present no algorithms have been developed for seeking a unique solution to such a problem.

The method of ray tracing[1] can be considered as most close by its realization to the algorithm sought. If the image size is, for example, 512 × 512 pixels, the calculation takes a long computer time and it is the problem for "large computers." However, for images of 16 × 16 pixels size such a problem can be solved using a PC.

Thus, for reconstructing the surface profile, whose image size is $N \times N$ pixels, this image should be divided into image cells of 16 × 16 pixels size. The disadvantage of this division is that breaks appear at the boundaries of the image cells resulting in an uncertainty in the orientation of microplates in separate image cells relative to each other.

In this paper we propose to remove this uncertainty in the following way:

– reconstruction of the surface relief begins starting from the center of one of the central image cells (cell *1* in Fig. 3);

– reconstruction of the surface relief in the cells (cells *2* in Fig. 3) having boundaries with the cell *1* begins at these boundaries and thus a possibility of breaks to appear at the boundaries is excluded because in this case the boundary values are rigorously set.

– after reconstructing the surface relief for the image cells *2*, the procedure of relief reconstruction is repeated for the cells *3*, *4* etc.

3	2	3	4
2	1	2	3
3	2	3	4
4	3	4	5

Fig. 3. Schematic presentation of stages of surface reconstruction, the cell number corresponds to the iteration number of reconstruction algorithm.

The technique of surface relief reconstruction based on measurement results on brightness of the optical image, obtained using a laser monitor, was checked using test two-dimensional images of three-dimensional objects with *a priori* known characteristics. The reconstructed reliefs are in a good qualitative agreement with the initial objects.

The evolutions of statistical characteristics of the graphite surface relief under the action of laser radiation were estimated with the use of the Herst statistics[4] for the image area close to the laser beam center. It should be noted that the Herst statistics is widely used in estimating complex mountain reliefs and surface roughness and also to determine the peculiarities of wave elevation distribution on the ocean surface.[4–6] The Herst index H was calculated according to the ratio

$$\frac{R(\Delta r)}{S(\Delta r)} \approx \Delta r^{H}, \qquad (1)$$

where $R(\Delta r)$ is the span, i.e., the difference between maximum and minimum heights measured at the distance Δr from the center along all radial directions, $S(\Delta r)$ is the standard deviation of heights, Δr is the dimensionless distance.

The ratio (1) determines the characteristic scale of the surface roughness. The Herst index value enables one to find the coefficient of correlation by the following formula[5–7]:

$$C(\Delta r) = 2^{2H-1} - 1, \qquad (2)$$

where H depends on Δr according to Eq. (1), $C(\Delta r)$ is similar to the correlation coefficient of two-dimensional random isotropic height distribution.[7]

According to Eq. (2) at $H = 0.5$ no correlation exists that corresponds to the Gaussian height distribution. However, at $H \neq 0.5$ we have $C(\Delta r) \neq 0$.

Results of reconstruction of the surface profile evolving under the action of laser radiation

Figure 4 shows the surface reliefs reconstructed based on the images shown in Fig. 1.

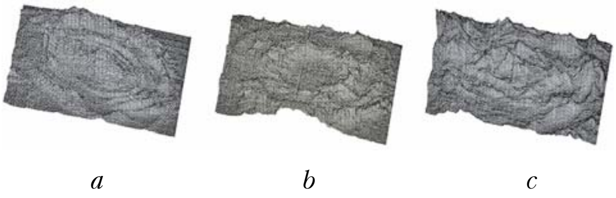

Fig. 4. Reconstructed reliefs of metal surface under the action of laser radiation: waves on the surface (*a*); turbulent splash of melt (*b*); expansion of turbulent zone (*c*).

To reconstruct the surface reliefs, the correlation coefficients given in the table were calculated. The values obtained allow us to separate numerically the conditions of the melt surface at different moments in time.

Table

Surface relief	Herst index H	Correlation coefficient $C(\Delta r)$
Waves on the surface	0.37	–0.165
Turbulent splash of melt	0.72	0.357
Expansion of turbulent zone	0.61	0.165

Conclusion

In this work the investigations have been carried out of the interaction of laser radiation with metal surface. The method of reconstruction of three-dimensional reliefs has been developed and realized using the two-dimensional surface image. Using the methods of fractal geometry the correlation coefficients of reconstructed reliefs were determined, the values of which enabled us to assess quantitatively the surface state.

Acknowledgments

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