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# A THEORETICAL AND EXPERIMENTAL METHOD FOR DETECTION OF THE DELAMINATIONS OF THIN COATINGS†

R. V. GOL'DSHTEIN, V. M. KOZINTSEV, A. L. POPOV and G. N. CHERNYSHEV

Moscow

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Theoretical and experimental methods for detection of thin coating delaminations from an elastic solid/substrate are presented. In the theoretical procedure, a beam model of the solid/substrate is used. Blistering of the coating is modelled by a half-circle of small radius over the central part of the beam. A bending load is modelled by a normal point force applied at the middle of the beam span. The experimental procedure is based on generating a bending stress-strain state in the solid, while recording the resulting displacements of the solid and the coating using the laser holographic interferometry and real-time and double-exposure methods [1, 2]. When the beam is loaded on the opposite side to the coating, displacement of points of the delaminated part of the coating occurs as a rigid whole in the direction in which the force acts in combination with longitudinal displacements owing to rotation of the beam cross-sections. This leads to a path difference in displacements of the beam sections with a tight- and loose-fitting coating. In a holographic comparison of the beam in different states, this difference in displacements is revealed in the form of local disturbances of the regularity of the system of fringes of the interferogram. © 2000 Elsevier Science Ltd. All rights reserved.

## 1. A BEAM MODEL FOR MONITORING THE SEPARATION OF THE COATING

Consider a beam of length $2l$, hinged at its edges (Fig. 1). The beam is covered by a thin coating with a small blister in the form of a half-circle of radius $a$ ($a \ll l$) in the central part of the beam. Assuming that the coating has no effect on the beam stiffness, we shall find the shape of the deflection of the beam with the coating when acted upon by a normal concentrated force $Q\delta(x)$ applied at the middle of the beam, as shown in Fig. 1.

The equation of the beam bending in terms of the deflection function $W(x)$ has the form

$$EJW''''(x) = Q\delta(x) \tag{1.1}$$

where $EJ$ is the bending stiffness and $x$ is the longitudinal coordinate with origin at the centre of the beam [3]. By direct integration we obtain

$$W(x) = \frac{Q}{12EJ}x^2|x| + \sum_{n=0}^{3} C_n x^n \tag{1.2}$$

($C_n$ are the integration constants). By virtue of the statement of the model problem, its solution should be symmetrical about the centre of the beam. Consequently, $C_1 = C_3 = 0$. The remaining constants are found from the boundary conditions

$$W(l) = 0, \quad W''(l) = 0$$

As a result, the shape of the deflection of the beam will take the form

$$W(x) = \frac{Q}{12EJ}(x^2|x| - 3lx^2 + 2l^3) \tag{1.3}$$

When the beam bends, points of the blistered area of the coating move in two directions.

First, they move as a rigid whole in the direction of the beam deflections. The magnitude of this displacement is equal to the elastic displacement of the ends of the blistered area, i.e. $W(a)$ (it is assumed

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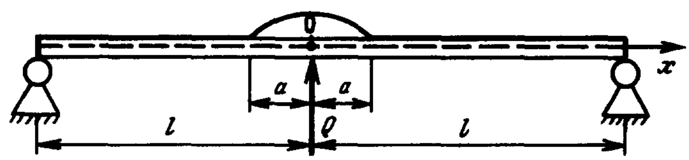


Fig. 1.

that the beam bending does not result in any further blistering of the coating). Relating the $x$ coordinate to the beam length, we obtain

$$W(a)=\frac{Ql^3}{12EJ}(\xi^3-3\xi^2+2),\quad \xi=\frac{a}{l} \tag{1.4}$$

If the coating were close-fitting over the entire length of the beam, the displacements of its points in the interval $a < x < a$ would differ from (1.4). At the central point ($x = 0$), the value of the displacement of the beam with the coating would be equal to $Ql^3/(6EJ)$. Consequently, the difference

$$\delta W = W(0) - W(a) \tag{1.5}$$

can be used as one of the indicators of blistering of the coating. Substituting expression (1.4) into (1.5), we obtain as a first approximation

$$\delta W = Ql^3\xi^3/(4EJ) \tag{1.6}$$

Secondly, displacement of the points where the coating is delaminated is also due to the longitudinal displacement of the ends of the blister owing to rotation of the beam cross-sections at bending. This leads to a change in the shape of the blister from a semicircle to a semi-ellipse elongated along the beam, with a reduction in the distance between the beam and the points where the coating is delaminated.

Mathematically, such an effect can be estimated through the change in curvature of the arc of the blister. Specifying the curvature of the arc of the beam axis by the well-known expression

$$\rho^{-1} \approx W''(x) \tag{1.7}$$

we obtain, for the centre of the beam, the value

$$\rho^{-1} \approx Ql/(2EJ) \tag{1.8}$$

For $a \ll 1$ it can be assumed that the curvature of the bent beam axis at the point $x = a$ is the same as at the point $x = 0$, i.e. is given by formula (1.8).

For the stretched layers of the beam with the coating, it is also necessary to take account of the change in the radius of curvature over the thickness of these layers. The radius of curvature of the outer layer of the beam will be $\rho_1 = \rho + h$, where $h$ is the half-thickness of the beam. Taking this into account and in view of the constancy of the length of the arc of the blister, calculated by means of the formula

$$s=2\int_0^a\left[1+\left(\frac{dW}{dx}\right)^2\right]^{1/2}dx$$

before and after deformation of the beam, we arrive at the value of the longitudinal displacement of the ends of the blister

$$\delta a=\frac{Qa}{2EJ}\left(1-\frac{a}{2}\right)\left(h+\frac{2EJ}{Ql}\right)-a \tag{1.9}$$

If the oval produced by drawing apart the ends of the semicircle is approximated by a semi-ellipse, its minor semiaxis will be equal to $a - da$. To a first approximation, the reduction in the blister opening is equal to $Qalh/(2EJ)$.

Combining the value obtained with the quantity (1.6) and referring them to the maximum deflection of the beam axis, we arrive at the final formula for the change in the blister opening as a result of bending compared with the undeformed state:

$$\frac{\delta a}{W(0)} = \frac{3}{2}\left(\frac{a}{l}\right)^2\left(1+\frac{2h}{a}\right) \tag{1.10}$$

In the holographic method of measuring the normal displacements of the beam, the change in the blister opening is revealed in the form of local disturbances of the regularity of the system of interferogram fringes, namely, the emergence, on the pattern of the levels of beam deflection, of plateau sections and fringe crowding. Formula (1.11) can be used to estimate the beam load required in the experiment, which, for prescribed beam dimensions and the proposed radius of the blister, ensures resolution of the interference fringes necessary to identify the delamination.

## 2. LASER INTERFEROMETRIC PROCEDURE FOR DELAMINATION DETECTION AT BENDING THIN BODIES WITH COATINGS

The principle of laser interferometric recording of the surface displacements of a body is as follows: holograms of the object that have been recorded at different times with the object in various states are compared (the double-exposure method) or a hologram of the object before the action and the object itself after the action are compared (the real-time method). Displacements of the object surface that have occurred as a result of the action are revealed in the form of an interferogram—a system of lines of equal displacements [1, 2].

To record blistering when thin bodies with coatings are bent, we used an optical scheme of reflection holography, on the basis of which an experimental unit was developed for the holographic recording of the normal component of the displacement vector of the body surface [4, 5].

Studies were carried out on a rectangular aluminium plate (150 × 25 × 1.3 mm), with which, when bent along the greater side, the theoretical beam model agreed well. Aluminium foil 0.015 mm thick was glued to one side of the plate to form a coating. The joint was formed by bonding. The thickness of the adhesive layer was 0.01–0.02 mm. When the coating was applied, defects in the form of small blisters of the order of several thicknesses of the coating were created artificially (at these points the adhesive interlayer was removed).

Experiments were carried out with the ends of the long side of the plate rigidly clamped. Loading was carried out by leverage, which ensured the application of a near-concentrated load (as in Fig. 1) in the middle part of the plate on the opposite side of the coating. The measuring unit consisted of a steel plate with a network of threaded holes to which the optical components, the supports of the plate and the loading device were fastened. The magnitude of the load was varied from 20 to 150 g.

The hologram obtained using reflection holography, was recorded in accordance with the given optical scheme (Fig. 2) [1, 4]: *1* is the support plate; *2* is the aluminium plate with the coating; *3* is the element of the loading device and *4* is the photographic plate. The collimated beam of the laser transmitted through the photographic plate is the reference beam. The beam reflected from the object onto the photographic plate is the object beam. The direction of illumination in Fig. 2 is shown by the arrows, and the direction of observation is represented by the camera symbol.

The experiment was carried out in the following sequence. The sample was clamped to a unit with attached supporting balls and catchers for positioning the holographic photographic plates. On the plates,

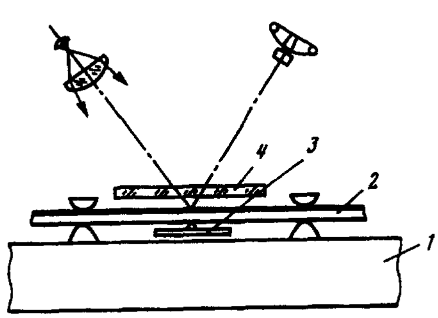


Fig. 2.

using a molten mixture of rosin and wax, a single steel ring catcher of the ball bearing was bonded. This enabled the plate with the hologram to be remounted in its former position. After aligning the optical system and secured fixing the position of all stationary components, the prepared plates were successively subjected to a first exposure for recording the unperturbed surface state of the sample. One of the exposed plates was developed immediately and, after washing and drying, was mounted in its original position and used as the reference hologram for observation in real time. During the second exposure, perturbed surface states of the sample were recorded on the remaining plates, i.e. double-exposure holograms were recorded. The normal displacements which occurred when a load is applied to the tested sample were recorded from the results of observations of the double-exposure holograms.

For an experimental determination of the relations between the load and the nature and position of the blisters in the coating and the form of the interference fringes, it was necessary to observe the change in the interference pattern during loading. This was done in real time using the reference hologram and enabled as to select the times at which the second exposure was made. As a result, on the same plate, two holograms were recorded successively: for the object in the initial state and after the action of the load. At the same time, recreation of both images by illuminating the developed photographic plate with a reference beam enabled us to observe and photograph the sample coated with a grid of interference fringes arising as a result of interference between the light waves forming images of the object in the initial and perturbed states. Each interference fringe determines the geometric position of points with equal values of the projection of the displacement vector onto the bisector of the angle between the directions of illumination and observation of the object.

When interference fringes due to displacements from loading appeared on the surface of the sample, observed as the reference hologram. The reference hologram was removed and another photographic plate was mounted, likewise exposed to the object in its initial state but undeveloped. The plate was then re-exposed. Thus, the interference pattern was recorded for the given load. After the reference hologram had been returned to its place, observation of the change in the interferogram when the load was increased was resumed before the next recording step.

On completion of the final loading step, ensuring a sufficient number of interference fringes in the interferometric pattern, the holograms obtained were mounted successively in a position which reproduced their arrangement when the pictures were taken. The image recreated by them was recorded by the camera.

Figure 3(a, b) presents interference fringes on the surface of the plate in the region containing blisters of the coating in two successive stages of loading the plate. The interferograms consist of parallel fringes resulting from deformation of the sample during bending, and annular fringes in the vicinity of local blisters. The position of the annular fringes coincides with the given defects. The relations between the sizes of the blisters along a normal to the plate surface, characterized by the number of annular fringes, can be clearly seen: one of them develops in two–three fringes, the others in one fringe. The dashed line in Fig. 3(c) shows the position of the photographed surface area of the plate with the coating (plan view).

Another characteristic of a blister is its linear dimensions along the plate surface. They are roughly the same as the dimensions of the largest annular fringe of the interferogram associated with the given defect. When the load increases (Fig. 3b) there is an increase in the number of parallel fringe. At the

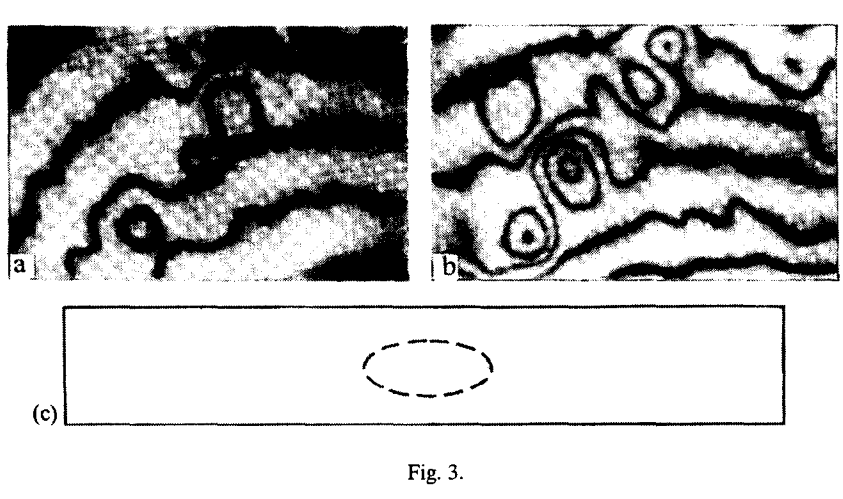


Fig. 3.

same time there is also an increase in the number of annular fringes at the revealed defects, and new annular fringes also appear in the vicinity of weaker blisters, not observed at the early stage of loading.

The number of successive stages of loading is limited by the requirement that there should be no loss of coating adhesion stability with respect to the initial state. The maximum load is chosen so that new defects do not occur and the linear dimensions of existing defects do not increase.

A comparison of experimentally visible interference fringes and their number on characteristic blisters in the case of a known fringe height gradient of $0.32\,\mu m$ with the results of calculations showed satisfactory agreement with a 20–30% discrepancy with respect to the overall dimensions of the blisters.

The investigation has shown the possibility of effective laser interferometric monitoring of the blistering of coatings by using a clear physicomathematical model of the appearance of such blisters, based on easily achieved bending deformations of thin bodies with coatings.

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