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ФИЗИКА ПРОЧНОСТИ И ПЛАСТИЧНОСТИ

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Modelling of Thin Films Hardness Measured by a Spherical Indenter

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In this theoretical contribution, we chose to use an indenter having a spherical geometrical form, which we used to model the surfaces mixture to separate the contributions of substrate and film in the composite covered material hardness. We have considered the coefficients α, β of the model as ratios of the projections of the imprints at the horizontal plans (disks surfaces). We prove that the film hardness of monolayer coating is dependent on the composite and substrate hardness, the geometrical form of the indenter, and the film thickness.

Key words: hardness, spherical indenter, model of the surfaces mixture, monolayer coating.

У цій теоретичній роботі розглянуто індентор сферичної геометричної форми, який було використано для складання моделю змішаних поверхонь, щоб оцінити внески підкладинки та плівки у твердість композитного матеріялу покриття. Коефіцієнти моделю α, β розглядаються як співвідношення проєкцій відбитків на горизонтальні площини (у вигляді дисків). Доведено, що твердість плівки одношарового покриття залежить від твердостей композитного покриття та підкладинки, геометричної форми індентора та товщини плівки.

Ключові слова: твердість, сферичний індентор, модель змішаних пове-

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рхонь, одношарове покриття.

В этой теоретической работе рассмотрен индентор сферической геометрической формы, который был использован для составления модели смешанных поверхностей, чтобы оценить вклады подложки и плёнки в твёрдость композитного материала покрытия. Коэффициенты модели α, β рассматриваются как отношения проекций отпечатков на горизонтальные плоскости (в виде дисков). Доказано, что твёрдость плёнки однослойного покрытия зависит от твёрдостей композитного покрытия и подложки, геометрической формы индентора и толщины плёнки.

Ключевые слова: твёрдость, сферический индентор, модель смешанных поверхностей, однослойное покрытие.

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1. INTRODUCTION

Surface treatments by coating or thin layers deposition were an effective way to control or improve many properties such corrosion resistance, electrical and decorative properties. However, surface characterization is mainly based on the measurement of micro- or nanohardness. This test gives the hardness of the coated layer H_f when it is thick enough; however, it involves substrate hardness H_s when it is more or less fine. Then, we consider the composite hardness H_c. Some authors have proposed a critical ratio indentation depth on the thickness of the coated layer to be able to separate the hardness of the coating from the substrate [1–3]. The weak point of this alternative lies in the variation of hardness as a function of indentation depth. On the other hand, the majority of experimental techniques, including ultramicrodurometry, have not shown good sensitivity with respect to the characterization of the behaviour of single layer [2, 4]. Measuring the indentation depth harsh layers under low load not exceeding a few millinewtons becomes insignificant. To circumvent these difficulties, different models have been proposed [4–16]. Several models offer an equation whose form can be written generally:

$$H_c = \alpha H_f + \beta H_s \text{ with } \alpha + \beta = 1.$$

Other more recent studies have taken into account further considerations: the plastic zone under indent [17] or the effect of the angle of indenter. These models have been validated on materials such as 316L (steel) or iridium. Experimental studies are used Berkovich or Vickers indenters where we must take into account the stress concentration at the top of the pyramid, on the one hand, and the effect of friction between the indenter and the material, on the other hand.

In this contribution, we have determined the coefficients α when the indenter is a sphere in function of the radius of the imprint r and indenter R, the film thickness e, and the function ε, then, the film hardness H_f in function of the composite hardness H_c, the hardness of substrate H_s, and the expression of balancing coefficient α.

2. MATHEMATICAL CONCEPT

Circles. In Cartesians coordinates (Oxy), the standard form of a circle equation of radius R [18] centred at the origin (Fig. 1, a) is given by the following equation:

$$X^2 + Y^2 = R^2. \tag{1}$$

Circle with radius R has an area of a disk S given by the formula

$$S = \pi R^2. \tag{2}$$

Spheres. A sphere is a perfectly round geometrical object that is three dimensional, with every point on its surface equidistant from its centre. The Cartesian equation of a spherical form of radius R (Fig. 1, b) centred at the origin is given [17] by

$$X^2 + Y^2 + Z^2 = R^2. \tag{3}$$

In the xOy plane, the radius of sphere r given by

$$X^2 + Y^2 = r^2. \tag{4}$$

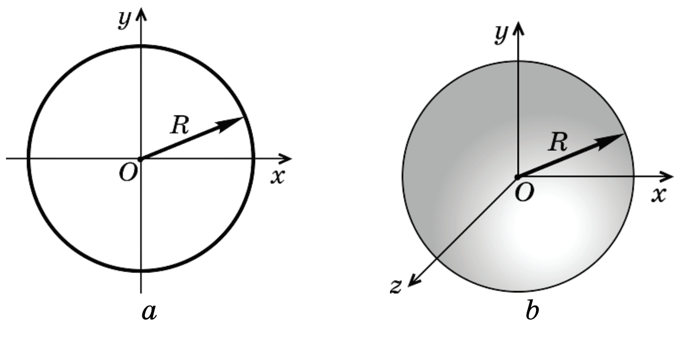

Fig. 1. Circle (a) and sphere (b) in Cartesians coordinates.

Therefore, the equation of sphere takes the formula

$$r^2 + Z^2 = R^2. \quad (5)$$

3. HARDNESS OF COVERED MATERIAL

3.1. Principe of Penetration

The principle consist to introducing a sufficiently hard indenter of spherical geometrical shape of radius R, in a covered material of a film thickness (e), under the action of a constant load (F) applied perpendicular to the indenter under definite conditions.

We measure the dimensions of the radius r of the transversals projected surfaces of the imprint. Consequently, we deduce the expression of the balancing coefficients of the surfaces mixture model law; then, we determine the hardness of film H_f according the composite hardness H_c, the hardness of substrate H_s, and the expression of balancing coefficient α.

3.2. Hardness and Penetration

In the statics tests of hardness [19–21], the hardness of massive material is defined by the report of the load F applied to the indenter on the projected surface of the imprint S:

$$H = F/S. \quad (6)$$

When the indenter has the spherical geometrical form, the projected surface of the imprint has a disk form of radius r [19–21]:

$$S = \pi r^2. \quad (7)$$

Then, the formula for hardness is as follows:

$$H = F/(\pi r^2). \quad (8)$$

According to the surfaces mixture model, the composite hardness of a monolayer coating (substrate + film) is given by the following additivity law [1, 12]:

$$H_c = \alpha H_f \ \text{ with } \alpha + \beta = 1, \quad (9)$$

where H_c and H_f are the hardnesses of substrate and film, respectively.

3.3. Balancing Coefficients

To separate the contributions of substrate and film on the composite hardness (film + substrate) of a monolayer coating measured according to the surfaces mixture model, the balancing coefficients (α, β) as ratios of projected surfaces of the imprints corresponding to an indenter of spherical geometrical form were expressed as follow [1, 12]:

$$\alpha = S_f/S_c, \quad \beta = S_s/S_c. \tag{10}$$

The projected surface of composite imprint (Fig. 2) is given by the expression

$$S_c = \pi r^2. \tag{11}$$

Therefore, the composite hardness is given by the following expression:

$$H_c = F/(\pi r^2). \tag{12}$$

Thus, the projected surface of imprint of the substrate (Fig. 2) becomes as follows:

$$S_s = \pi r_0^2, \tag{13}$$

and the projected surface of film is given by the following formula:

$$S_f = S_c - S_s = \pi(r^2 - r_0^2). \tag{14}$$

According to the law of the surfaces mixture (9), the composite hardness for the monolayer coating is given by the following additivity law:

$$H_c = \alpha H_f + (1-\alpha)H_s \tag{15}$$

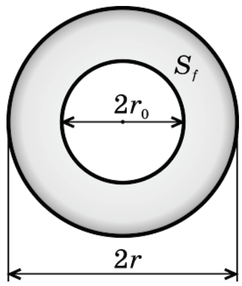

Fig. 2. Load-supporting areas of film and substrate of spherical indenter.

with

$$\alpha = S_f / S_c = (r^2 - r_0^2) / r^2. \quad (16)$$

From Eq. (5) and for the point (r_0, h_0) in the rOz plane (Fig. 3), we obtain

$$r_0^2 + h_0^2 = R^2 \Rightarrow r_0^2 = R^2 - h_0^2. \quad (17)$$

From Eq. (5) and for the point (r, h) in the rOz plane (Fig. 3), we also obtain

$$r^2 + h^2 = R^2 \Rightarrow r^2 = R^2 - h^2. \quad (18)$$

The subtraction Eq. (17) from Eq. (18) gives the following equation:

$$r^2 - r_0^2 = h_0^2 - h^2. \quad (19)$$

Replacing Eq. (19) into Eq. (16), we get:

$$\alpha = (r^2 - r_0^2) / r^2 = (h_0^2 - h^2) / r^2, \quad (20)$$

and besides, we have

$$h_0^2 - h^2 = (h_0 - h)(h_0 - h + 2h). \quad (21)$$

From the geometric model in Fig. 3, it is clear that the thickness length of deformed film $(h_0 - h)$ is dependent on the film thickness

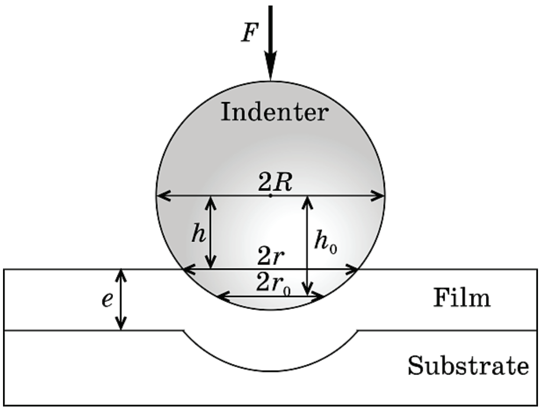

Fig. 3. Representation of spherical penetration in the xOz plane.

(e), the imprint radius (r), and the sphere radius (R). Therefore, we can consider that the thickness of deformed film is given by the following relation:

$$h_0 - h = \varepsilon. \quad (22)$$

Here, ε is a function of parameters e, r, R.

By introducing Eq. (22) into Eq. (21), we get:

$$h_0^2 - h^2 = (h_0 - h)(h_0 - h + 2h) = \varepsilon(\varepsilon + 2h). \quad (23)$$

From Eq. (18), one can find

$$h = \sqrt{R^2 - r^2}. \quad (24)$$

When we replace Eq. (24) in Eq. (23), we get:

$$h_0^2 - h^2 = \varepsilon(\varepsilon + 2\sqrt{R^2 - r^2}). \quad (25)$$

For the microhardness, the imprint is small; thus, the length of deformed film is negligible ($\varepsilon^2 \approx 0$), and we can write:

$$h_0^2 - h^2 \approx 2\varepsilon\sqrt{R^2 - r^2}. \quad (26)$$

When we substitute Eq. (25) into Eq. (20), the balancing coefficient α becomes, according to the indenter radius R, the film thickness e, and the radius r of the composite projected surface, as follows:

$$\alpha = 2\varepsilon\sqrt{R^2 - r^2} / r^2. \quad (27)$$

From Eq. (17), the film hardness H_f becomes, according to the composite hardness H_c, substrate hardness H_s, and the balancing coefficient α, as follows:

$$H_f = [H_c - (1 - \alpha)H_s] / \alpha. \quad (28)$$

By introducing the value of the balancing coefficient α in Eq. (28), the film microhardness H_f becomes, according to the experimentally given H_c, H_s, r, the radius of the spherical indenter R, the value of the quantity ε, as follows:

$$H_f = \frac{H_c - (1 - 2\varepsilon\sqrt{R^2 - r^2} / r^2)H_s}{2\varepsilon\sqrt{R^2 - r^2} / r^2} = H_s + \frac{r^2(H_c - H_s)}{2\varepsilon\sqrt{R^2 - r^2}}. \quad (29)$$

Thus, in the case of nanohardness, the imprint was very small; so, its radius is negligible ($R >> r$), and the balancing coefficient becomes as follows:

$$\alpha = 2\varepsilon\sqrt{R^2 - r^2} / r^2 = 2\varepsilon R / r^2. \tag{30}$$

When we introduce Eq. (30) into Eq. (28), we get

$$H_f = \frac{H_c - (1 - 2R\varepsilon / r^2)H_s}{2R\varepsilon / r^2} = H_s + \frac{r^2(H_c - H_s)}{2R\varepsilon}. \tag{31}$$

4. CONCLUSION

The conclusions of this work may be summarized as follow.
1. In this study, we proposed geometrical approach of the balancing coefficients of the model of surfaces mixture, where the indenter has a spherical geometrical form. Thus, it was supposed that the thickness of deformed film is given by the following relation: $h_0 - h = \varepsilon$ with $\varepsilon < e$.
2. We conclude that the film hardness depends on experimental measurements such as composite hardness H_c, substrate hardness H_s, imprints radius r, the film thickness e, and the radius of the spherical indenter R.
3. The function ε is dependent on the film deformation and the form and dimensions of indenter. Their expression can be fined by geometrical moulding (and it can be verified by the experimental tests).
4. We believe that our contribution have a new theoretical and, perhaps, experimental interest to the mechanical characterization of the covered materials, which will bring to widen the field of application of the hardness tests.

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