

# Nanocrystalline coatings properties forecasting

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**Abstract.** The paper considers various properties of nanocrystalline coatings. The methods of determining the surface tension of the deposited coating on the basis of the size dependence of their physical properties. It is shown that predict the mechanical properties of the coatings, their melting point, heat resistance, wear resistance, corrosion resistance, etc. It can be based on a theoretical evaluation of the surface tension.

## 1. Introduction

In the literature reviewed various methods of depositing nanostructured films [1]. However, most of the work is devoted to the traditional methods of film deposition: vapor deposition and plasma. The most promising for nanostructured coatings are vacuum ion-plasma methods: magnetron sputtering, ion and vacuum arc deposition. This is due to the fact that in addition to thermal factors there are other - high degree of ionization and the energy flux density of the particles.

Although methods for producing nanostructured materials and coatings are quite diverse, but they all are based on the mechanism of energy dissipation of intense, generalized in the three stages of formation. The first stage is a process of nucleation, which is due to lack of appropriate thermodynamic conditions, will not go into mass crystallization. The second step is the formation of nuclei around nanocrystalline amorphous clusters, which - in a third step - are combined in the intergranular phase to form a dissipative structure.

Each of these steps is a complex process. Suffice it to point out the process of nucleation of a new phase, a theory which has been developing for more than 100 years old, and wasps main points of which were laid by Gibbs and then developed by Volmer, Becker and Doering, and Stransky Kaishevym, Frenkel, Zeldovich.

Even more difficult is the third stage of the formation of the coating, when the growth of the film is determined by the condition, on the mobile interface. Such problems are called «problem Stefan» [2]. The above difficulties do not allow us to construct a rigorous theory of the formation of plasma coatings to date, including nanocrystalline coatings, where, along with the classic problems arise and the problems of the account size effects in the formation of new phase nuclei.

All this affects the prediction of plasma coating properties [3].

## 2. Formulation of the problem

In recent years, the concept has evolved high-entropy or multi-element alloys and coatings based on them [4].



The stability of the structure and composition, as well as high performance systems high-entropy create very attractive possibility of the formation based on these coatings in order to improve the surface characteristics or use them as protective films that prevent harmful impurities in the surface layers.

However, the quantitative theory of these effects yet. In the present work shows the possibility of predicting certain important properties of nanostructured coatings multielement.

### 3. Theory

In [5, 6], we have demonstrated the possibility of experimental determination of the surface tension of coatings deposited by the size dependence of their properties.

We used the method of measuring the surface tension by determining the dependence of the microhardness on the thickness of the deposited coating. The dependence of the microhardness of the deposited coating on its thickness is described by the formula [5]:

$$\mu = \mu_0 \cdot \left(1 - \frac{d}{h}\right), \quad (1)$$

where  $\mu$  - micro hardness of deposited coatings;  $\mu_0$  - micro hardness «fat» sample;  $h$  - thickness of the deposited coating.

The parameter  $d$  is associated with a surface tension  $\sigma$  formula [5]:

$$d = \frac{2\sigma v}{RT}, \quad (2)$$

Here  $\sigma$  - the surface tension of the bulk sample;  $u$  - volume of one mole;  $R$  - gas constant;  $T$  - temperature.

The coordinates  $\mu \sim 1/h$  ( $1/h$  - reverse deposited coating thickness) obtained straight line the slope of which determines the  $d$ , and formula (2) is calculated as the surface tension of the deposited coating ( $\sigma$ ).

One can use any size dependence of the properties of  $A(r)$  coatings (electrical conductivity, magnetic susceptibility, etc.), which are described by the equation:

$$A(r) = A_0 \cdot \left(1 - \frac{d}{h}\right). \quad (3)$$

In [7] defined by the surface tension of the pure metals. The results are shown in Table 1.

**Table 1.** Surface tension of pure metals (M) at a temperature of 300 K [7]

M	$\sigma, \text{J/m}^2$	M	$\sigma, \text{J/m}^2$	M	$\sigma, \text{J/m}^2$
Li	0,152	Sr	0,730	Sn	0,205
Na	0,071	Ba	0,683	Pb	0,300
K	0,037	Al	0,633	Se	0,193
Rb	0,012	Ga	0,003	Te	0,425
Cs	0,002	In	0,129	Cu	1,056
Be	1,258	Tl	0,276	Ag	0,934
Mg	0,623	Si	1,386	Au	1,036
Ca	0,818	Ge	0,931	Zn	0,399
Cd	0,294	Fe	1,508	Gd	1,285
Hg	0,07	Co	1,463	Tb	1,331
Cr	1,873	Ni	1,426	Dy	1,380
Mo	2,573	Ce	0,777	Ho	1,434

W	3,373	Pr	0,908	Er	1,470
Mn	1,217	Nd	0,998	Tm	1,518
Tc	2,173	Sm	1,025	Yb	0,797
Re	3,123	Eu	0,875	Lu	1,625

#### 4. Experimental results

The surface tension of the coating Zn-Cu-Al was determined by the method described above. A quantitative analysis of the elemental composition of the composite coating was carried out on JEOL JSM-5910 electron microscope. Results stoichiometry calculation gave the following result:  $Zn_{0,59}Cu_{0,01}Al_{0,40}$ . The mean value of the surface tension is equal to:  $\sigma_{Zn-Cu-Al} = 0,351 \text{ J/m}^2$ . The surface properties of coatings in most cases correspond to the principle of additivity. Then, the condition:

$$\sigma_{Zn_{0,59}Cu_{0,01}Al_{0,40}} = 0,59\sigma_{Zn} + 0,01\sigma_{Cu} + 0,40\sigma_{Al}. \quad (4)$$

Using the data in Table I for  $\sigma_{Zn}$ ,  $\sigma_{Cu}$  and  $\sigma_{Al}$ , obtain  $\sigma_{Zn-Cu-Al} = 0,412 \text{ J/m}^2$ . Experimental and theoretical values for the coating Zn-Cu-Al were close to each other: ( $\sigma_{Zn-Cu-Al} \approx 0,4 \text{ J/m}^2$ ). Similar measurements were carried out for a number of multi-coatings. The equation of the type (4) turned out to be true for all investigated coatings.

This result leads to the following important conclusion: using the additive property of the surface tension, it is possible to select components of the coating so as to increase or decrease the surface tension of the coating compared to pure metals.

Experimental study of mechanical properties of nanomaterials and nanostructured coatings showed that the tensile strength, hardness, many metals (Pd, Cu, Ag, Ni et al.) is significantly higher than the corresponding bulk analogs [8]. Increased strength and hardness with decreasing grain size up to a certain critical size is typical for virtually all crystals. This follows from the known Hall-Petch equation that yield strength  $\sigma_T$  depends inversely on the average grain size  $d$  [8]:

$$\sigma_T = \sigma_M + kd^{-1/2}, \quad (5)$$

where  $\sigma_M$ - the limit strength of the single crystal,  $k$  - coefficient of some dimension.

Typically, Hall-Petch relationship (5) is performed for a large part of the nanomaterials studied only up to a certain grain size, while at lower values it is bucking the effects of hardness (strength) decreases with decreasing grain size.

Despite the large number of studies on the influence of the size factor on the mechanical properties of nanostructures, the physical mechanisms of this effect remain the subject of ongoing discussions. A comprehensive review of the problem is given in [8]. In [9], an equation for the yield point:

$$\sigma_T = \sigma_M + C\sigma d^{-1/2}. \quad (6)$$

Equation (6) coincides in shape with the Hall-Petch equation (5). However, the coefficients of proportionality differ in both formulas. In the case of the equation (6) the behavior of the yield strength of small particles is also determined by the size of their surface tension  $\sigma$ .

For small  $d$  Rusanov got asymptotic linear relationship [10]:

$$\sigma = Kd. \quad (7)$$

Here  $K$  - coefficient of proportionality.

Formula (7) is obtained on the basis of thermodynamic consideration and should be applicable to small objects of various nature.

In this case, the equation (6) takes the form:

$$\sigma_T = \sigma_M + CKd^{1/2}. \quad (8)$$

Equation (8) represents the opposite effect Hall-Petch.

From equation (6) that the Hall-Petch equation begins to be violated from the moment when it begins to appear the size dependence of the surface tension.

## 5. Discussion

In [11] it is shown that for pure metals with high accuracy, the relation:

$$\sigma = 0,7 \cdot 10^{-3} \cdot T_m, \quad (9)$$

where  $T_m$  - melting point metal.

Taking into account the additive coating the surface tension, the equation (9) can be rewritten as:

$$\dot{\sigma}_{ie} = 1,4 \cdot 10^3 \cdot \sigma \text{ (K)}. \quad (10)$$

As an example, Table 2 shows the melting temperature multielement coatings obtained while spraying us various cathodes.

**Table 2.** Melting point multielement coatings obtained in argon

Coating	$T_m$ , K	Coating	$T_m$ , K
12X18H10T+Zr	1358	12X18H10T+Zn-Al	1537
12X18H10T+Zn-Cu-Al	1530	12X18H10T+Al	1602
12X18H10T+Fe-Al	1809	12X18H10T+Cu	2023

Steel melting temperature depends on their chemical composition, but is in the range (1450 - 1520) K. As seen from Table 3 the coating 12Cr18Ni10Ti+Al, 12Cr18Ni10Ti+Fe-Al and 12Cr18Ni10Ti+Cu on the melting temperature significantly superior to many steel.

Currently refractory coating deposition is carried out mainly by arc or magnetron vacuum methods. Thus, various target compounds comprising metals such as chromium, titanium, zirconium in combination with non-ferrous metals. We investigated the coating deposited by ion-plasma method while spraying steel cathode 12Cr18Ni10Ti and composite cathodes. Method for determination of heat resistance is based on GOST 6130-71. The experimental results are presented in the table 3.

**Table 3.** Loss of coating weight, resulting in an argon atmosphere, after heat treatment at 600 ° C for 100 hours

Coating	Weight oxidized coating, mg
A sample of uncoated, steel 45	56,8
12Cr18Ni10Ti+Zr	24,4
12Cr18Ni10Ti+Zn-Cu-Al	14,4
12Cr18Ni10Ti+Fe-Al	5,6
12Cr18Ni10Ti+Zn-Al	14,2
12Cr18Ni10Ti+Al	4,8
12Cr18Ni10Ti+Cu	56,8

From a comparison of the results of Tables III and I, the conclusion: the greater the surface tension of the coating, the greater its heat resistance. If the heat resistance mark -  $\zeta$ , then said mathematically can be expressed as a functional relationship:

$$\zeta = f(\sigma) = C \cdot \sigma, \quad (11)$$

where  $C$  - a constant.

Anti-corrosion coatings obtained by magnetron method considered in [11-14]. In cases where the corrosion process proceeds as general corrosion, a change in the amount of metal can be used for evaluating corrosion rates in a process changing the amount of the reaction agent (oxidant), or one of the products of corrosion over time. Since the corrosion process is heterogeneous, the appropriate quantitative characteristics should be attributed to the surface of the unit.

Table 4 shows the corrosion rate at 600 °C studied coatings, which was determined by the formula:

$$v_{\kappa} = \Delta m / S \cdot t, \quad (12)$$

where  $\Delta m$  - decrease (increase) in weight;  $S$  - area of the sample;  $t$  - time.

From the comparison results tables IV and I, the conclusion: the greater the surface tension of the coating, the greater the corrosion resistance. If corrosion resistance mark -  $\chi$ , then said mathematically be written as:

$$\chi = f(\sigma) = C_1 \cdot \sigma, \quad (13)$$

where  $C_1$  - a constant.

**Table 4.** The corrosion rate at 600 °C the coating obtained in argon

Coating	The corrosion rate, g/m <sup>2</sup> h
A sample of uncoated, steel 45	2,84
12Cr18Ni10Ti+Zr	1,22
12Cr18Ni10Ti+Zn-Cu-Al	0,72
12Cr18Ni10Ti+Fe-Al	0,28
12Cr18Ni10Ti+Zn-Al	0,71
12Cr18Ni10Ti+Al	0,24

The wear resistance of the coating is determined by the work of her destruction, which is equal to:

$$A = \sigma \cdot S, \quad (14)$$

where  $S$  - area of the sample surface.

As an example, in Table 5 shows the results of calculation of the fracture coating ( $S = 1 \text{ m}^2$ ) from the experimental value of the surface tension  $\sigma$ .

**Table 5.** Job destruction of some multi-element coatings

Coating	Energy destruction coating, J.
Zn-Cu-Al	2,43
Cr-Mn-Si-Cu-Fe-Al	7,11
Mn-Fe-Cu-Al	3,67

## 6. Conclusion

It follows from the above results that the majority of properties of the coatings is determined by their surface tension (surface energy). Using Table 1 and obtained in the ratio, it is possible to predict the performance properties of coatings based on their functionality.

Currently there is no quantitative theory that allows to predict the desired properties of the coating, depending on the technological conditions, the materials used and the target cathodes, etc. Therefore,

even high quality models proposed in this paper can help prevent a large volume of routine, but expensive works.

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