East European Journal of Physics. 4. 298-302 (2023)
DOI:10.26565/2312-4334-2023-4-38 ISSN 2312-4334

OPTICAL PARAMETERS OF ALUMINUM ALLOY SAMPLES IRRADIATED BY HIGH CURRENT RELATIVISTIC ELECTRON BEAMS

Mykola O. Azarenkov[a,c], Oleksii A. Haluza[b], Alexander V. Gapon[c]*, Volodymyr V. Lytvynenko[d]
[a] *National Science Center Kharkiv Institute of Physics and Technology, Institute of Solid-State Physics, Materials Science and Technologies, 1, Akademicheskaya St., Kharkiv, 61108, Ukraine*
[b] *National Technical University "Kharkiv Polytechnic Institute", 2 Kyrpychova St., Kharkiv, 61002, Ukraine*
[c] *V.N. Karazin Kharkiv National University, 4, Svobody Sq., Kharkiv, 61020, Ukraine*
[d] *Institute of Electrophysics and Radiation Technologies NAS of Ukraine, Chernyshevsky St., 28, 61002 Kharkiv, Ukraine*
**Corresponding author e-mail: gapon@karazin.ua*
Received October 1, 2023; revised November 7, 2023; accepted November 17, 2023

The aluminum alloys D16, D16AT are widely used as construction materials in the aircraft industry. Questions connected with the enhancement of the properties of the construction elements made of the alloys through surface modification are of great interest now. The objects of the study in our paper are the samples of the aluminum alloy D16AT subjected to irradiation by high-current relativistic electron beams. Leaving aside the material science aspects, in this work we focused on modeling the optical properties of the samples. The problem is relevant because optical methods for surface analysis have become widespread due to their versatility and efficiency. Through the treatment of the preliminary measured ellipsometry data, we obtain the optical constants of the samples and their dispersion in the visible region of wavelength. The method used consists of an approximation of the reflection coefficient calculated from the ellipsometry data by finding the values of the parameters in the model. The last is performed by the least squares method. The reflection coefficient is assumed to correspond to the semibounded uniaxial medium with the optical axis perpendicular to the interface between the medium and the homogeneous and dielectric ambient medium. The dielectric function of the semibounded medium is approximated by the Drude-Lorentz model. The possibility of birefringence of the samples caused by the irradiation with electron beams is discussed.
Keywords: *Electron beam treatment, Aluminum alloy, Optics of metals, Ellipsometry*
PACS: 07.60 Fs, 61.80.Fe

INTRODUCTION

The electron beam techniques are interesting for processing and modification of a wide range of materials and possess such useful features as energy effectivity, versatility and short technological process time.

Irradiation by electron beams becomes the widespread and effective technology used for modification of a metal surface. In particular, hardness, wear and chemical resistivity can be improved due to changes followed the electron beam impact, such as refinement of grain structure and solid phase transformation. Investigations in this field are intensively continued. Comprehensive reviews of the studies are [1], [2]. Besides traditional applications for structural materials, it can be pointed out to the studies of electron beams for the treatment of textile materials [3] and food [4]. The paper [5] gives a survey of the applications in the rapidly growing additive manufacturing. The paper [6] reports enhancing a film of organic-inorganic hybrid perovskite by electron beam irradiation to use it in LED applications. In [7] the influence of an electron beam surface treatment on the dislocational substructure of high-entropy alloys was investigated.

In addition, combined technologies acquire widespread use. It is worthwhile to mention sprayed coating and electron beam remelting treatments in the first wall of nuclear fusion devices [8], and a combined treatment of a porosity polyamide coating by the laser and electron beams to make it waterproof [9].

The methods of the analysis and the process control have great importance for the technology. In the framework of the simple model of a semibounded medium, we analyze rotating analyzer ellipsometry (RAE) data [10] to study D16AT alloy samples exposed to high current relativistic electron beams.

THEORETICAL MODEL

We consider a linear absorbing medium characterized by a dielectric function ε. The refraction coefficient is expressed via the dielectric function as follows:

$$n = \nu - \mathrm{i}\kappa = \sqrt{\varepsilon}\ , \tag{1}$$

where ν and κ are the real and imaginary parts of the refraction coefficient. The dielectric function of metals in the visible and infrared wavelength ranges is satisfied well with the Drude-Lorentz model and can be approximated as

$$\varepsilon = 1 - \frac{f_0\omega_p^2}{\omega(\omega - \mathrm{i}\Gamma_0)} - \sum_j \frac{f_j\omega_p^2}{\omega(\omega - \mathrm{i}\Gamma_j) - \omega_j^2}\ . \tag{2}$$

Cite as: M.O. Azarenkov, O.A. Haluza, A.V. Gapon, V.V. Lytvynenko, East Eur. J. Phys. 4, 298 (2023), https://doi.org/10.26565/2312-4334-2023-4-38

In fact, the medium response is presented here as the sum of the impacts of the non-interacting oscillators, in which ω is the wave frequency; f_0, f_j are the strengths of the oscillators; ω_p is the free electrons plasma frequency; ω_j are the frequencies of the oscillators; and Γ_0, Γ_j are the inverse lifetimes of the oscillators [11]. We assume that the expressions (1) and (2) are also acceptable for the ordinary and extraordinary refraction coefficients n_o and n_e of a birefringent uniaxial medium. This is the case when the principal axes of the permittivity tensor coincide with those of the conductivity tensor of the medium.

The Jones vector determines a fully polarized beam uniquely. It is formed from the complex electric field components parallel (E_p) and perpendicular (E_s) to the incidence plane. In the general case, a reflection of the polarized beam from the surface of the birefringent medium can be described by the reflection coefficients r_{pp}, r_{ps}, r_{sp}, r_{ss}, combined in the Jones matrix of the reflected surface:

$$\begin{pmatrix} E_{ip} \\ E_{is} \end{pmatrix} = \begin{pmatrix} r_{pp} & r_{ps} \\ r_{sp} & r_{ss} \end{pmatrix} \begin{pmatrix} E_{rp} \\ E_{rs} \end{pmatrix}. \tag{3}$$

The indexes "*i*" and "*r*" mark the incident and reflected waves, correspondingly. In ellipsometry, however, only relative values of the reflection coefficients are considered. Usually, the coefficients are referenced to the coefficient r_{ss}. Denoting these normalized values through ρ_{pp}, ρ_{ps}, ρ_{sp}, we can rewrite the expression (3) as:

$$\begin{pmatrix} E_{ip} \\ E_{is} \end{pmatrix} = r_{ss} \begin{pmatrix} \rho_{pp} & \rho_{ps} \\ \rho_{sp} & 1 \end{pmatrix} \begin{pmatrix} E_{rp} \\ E_{rs} \end{pmatrix}, \tag{4}$$

In the study, we assume that the optical axis of the birefringent sample is perpendicular to the surface. Then, the r_{ps} and r_{sp} coefficients drop out, while the diagonal elements are [12]:

$$r_{ss} = \frac{E_{rs}}{E_{is}} = \frac{\cos\varphi - (n_o^2 - \sin^2\varphi)^{1/2}}{\cos\varphi + (n_o^2 - \sin^2\varphi)^{1/2}}, \tag{5}$$

$$r_{pp} = \frac{E_{rp}}{E_{ip}} = \frac{n_o n_e \cos\varphi - (n_e^2 - \sin^2\varphi)^{1/2}}{n_o n_e \cos\varphi + (n_e^2 - \sin^2\varphi)^{1/2}}, \tag{6}$$

$$\rho_{pp} = r_{pp} / r_{ss}, \tag{7}$$

where φ is the angle of incidence and n_o, n_e are the refraction indexes regarding the ambient medium. Therefore, only one coefficient, ρ_{pp}, encapsulates all the ellipsometry data in this case. When the birefringence of the sample vanishes, the values r_{ss} and r_{pp} tend to the r_s and r_p of the isotropic medium as the refractive indexes n_o, n_e tends to the isotropic refraction index n. Then the coefficient ρ_{pp} reads as follows:

$$\rho_{pp}^0 = \frac{\sin^2\varphi - \cos\varphi(n^2 - \sin^2\varphi)^{1/2}}{\sin^2\varphi + \cos\varphi(n^2 - \sin^2\varphi)^{1/2}}. \tag{8}$$

ROTATING ANALYZER ELLIPSOMETRY

Let us consider the typical diagram of the RAE instrument shown in Figure 1. The beam emitted by the source passes through the polarizer **P** to obtain linear polarization, reflects from the sample surface, passes the analyzer **A**, and is photometrized. The angle of incidence of the beam φ can vary.

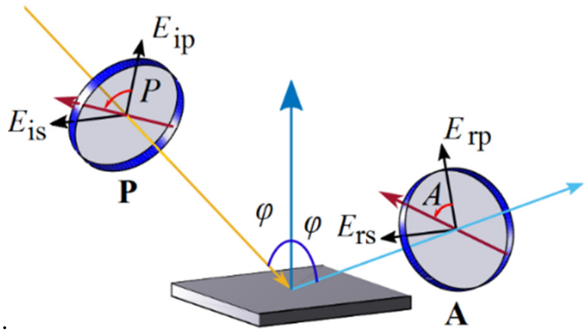

Figure 1. The sketch of the typical rotating analyzer ellipsometry instrument

In addition, the spectral analysis of the beam is performed, which allows to determine the dependence of the ellipsometry parameters on the wavelength. The detector output $I(t)$ varies with the time t as

$$I(t) = I_0(1 + \alpha\cos 2\omega t + \beta\sin 2\omega t), \tag{9}$$

where $A=\omega t$ is the rotating analyzer turn angle. The values α and β give the ellipsometry parameters ψ and Δ:

$$\tan\psi = \sqrt{\frac{1+\alpha}{1-\alpha}}\,|\tan P|, \qquad \cos\Delta = \frac{\beta}{\sqrt{1-\alpha^2}}. \tag{10}$$

To extract the reflection coefficient ρ_{pp} only valid in our case, we can set the polarization azimuth P of the polarizer to 45°, so modules of the complex amplitudes E_{ip} and E_{is} of the incident beam become equal. In this condition

$$\tan\psi\, e^{i\Delta} = \frac{E_{rp}}{E_{rs}} = \frac{E_{rp}/E_{ip}}{E_{rs}/E_{is}} = \frac{r_{pp}}{r_{ss}} = \rho_{pp}. \tag{11}$$

In contrast, for an arbitrary orientation of the optical axis of the sample, when the Jones matrix of the reflected surface is off-diagonal, we should change the azimuth P of the polarizer to obtain at least three pairs of (ψ, Δ) determining the coefficients ρ_{pp}, ρ_{ps}, ρ_{sp}.

Expressions (11), (7) and (8) set the interrelation between the measured ellipsometry parameters ψ, Δ and the constants of the optically uniaxial medium n_o, n_e. Obviously, to determine the set of four unknowns, consisting the real and imaginary parts of n_o and n_e, we need at least two different measurements of the set of two ellipsometry parameters (ψ, Δ). They are made by the incident angle φ changing. As experimental data contain measurement errors, all the points $(\psi, \Delta)_k$ corresponded to the different incident angles φ_k should be considered to extract the values of the refractive coefficients. By the least squares method, we find the values of refractive indexes n_o, n_e, for which the objective function f reaches its minimum:

$$f = \sum_k \left|\rho_{\mathrm{pp}}(\varphi_k) - \tan\psi_k \exp(\mathrm{i}\Delta_k)\right|^2 \to \min. \tag{12}$$

SAMPLES STUDIED

This work deals with the samples made from the D16AT aluminum alloy obtained during the wide investigations performed to study a modification of the surface of a metal target by the high current pulsed relativistic electron beams.

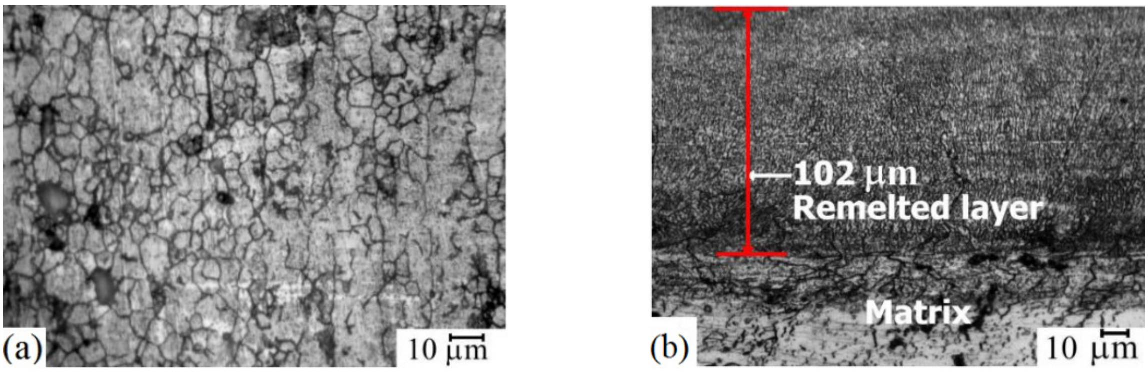

Figure 2. The D16AT aluminum alloy microstructure before (a) and after (b) the irradiation [14].

Details of the preparation, processing, and postprocessing of the samples are presented in the works [13], [14], and [15]. Generally, the interaction of the beams with metal targets represents a rather complex sequence of processes, initiated by radiation and ionization energy losses of particles. This leads to a change in the essential operational properties of the surface layer of irradiated samples, such as plasticity, corrosion and erosion resistance, hardness, etc. Exposure to the electron impact results in the refinement of the grain structure down to nanoscale sizes [14], the redistribution of elements at grain boundaries [15], etc. Figure 2 shows the changes in the surface layer of the D16AT alloy sample due to the electron beam impact. In Figure 2(b), the remelted layer about 100 microns in depth is visible, which is characterized by the modified structure and phase composition. Particularly, the average grain size is reduced from 11 µm to 0.8 µm, concentrations of the alloy dopes rise by 1–3 wt% compared to the matrix values, and the dislocation density becomes eight times greater.

High levels of pressure and temperature gradients during short-term (~1 µs) processing suggest that the sample surface layer can obtain properties of an optically uniaxial medium. The model of a semibounded uniaxial medium should be acceptable due to the smallness of the skin depth of metals in the visible region in comparison with the layer depth. Figure 3 shows the angular dependencies of the ellipsometry parameters of three samples denoted as K1, K2 and K3 [10]. Sample K1 was not subjected to any radiation effects; sample K2 was irradiated with the electron beam incident perpendicular to the surface; and sample K3 was irradiated at an angle of 45° to the surface. All the samples were made from the same workpiece and polished in the same way.

We tried both isotropic and uniaxial models to approximate the data. It turns out that the minimum of the objective function (12) achieved in the assumption of $n_o = n_e = n$ can be improved in the framework of the uniaxial model. For now, we have only the ellipsometry data reconstructed from the experimental graphs, which are out of the instrumental accuracy of 10′ [10]. It makes the results ambiguous, and then the uniaxiality of the samples remains under question. Figures 3(a), 3(b) show the angular dependencies of the ellipsometry parameters, measured at the wavelength of 633 nm. The curves corresponding to the two models nearly coincide on such large-scale plots, so the curves for the isotropic model are presented. The approximation of the angular dependencies gives the following isotropic refractive index values for samples K1, K2 and K3, respectively: 1.03 - 4.51i, 1.23 - 4.33i, 1.31 - 4.25i. The approximation of the spectral dependencies shown in figures 3(c), 3(d) gives information about the parameters of the Lorentz-Drude model (2), presented in Table 1. The data was measured with the fixed incident angle of 72°.

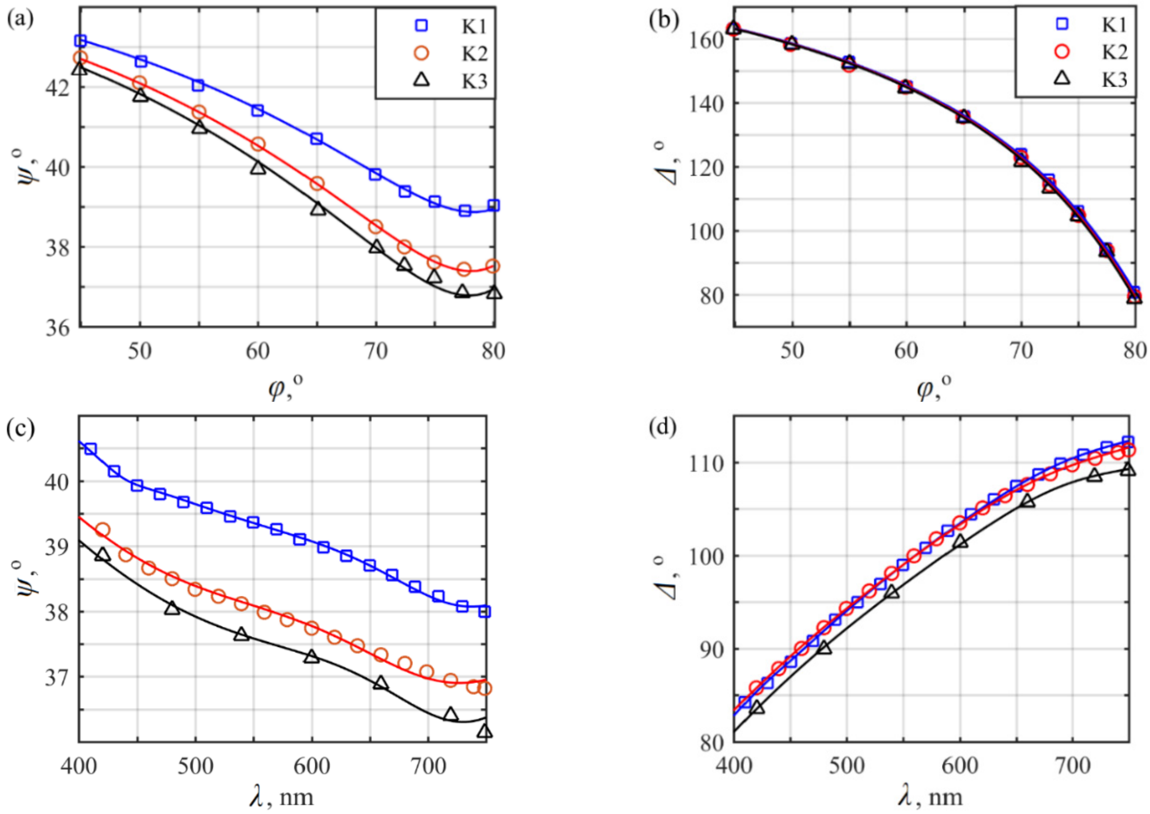

Figure 3. Angular (a), (b), and spectral (c), (d) dependencies of the ellipsometry parameters.

Table 1. Parameters of the Lorentz–Drude model (2) for the different samples. Column *Al* contains parameters for aluminum [12]; columns K1, K2, K3 contain parameters for corresponding samples of D16AT alloy. Calculations were performed in the isotropic approximation. The frequencies ω_p, ω_j and inverse lifetimes Γ_0, Γ_j are presented in the energetic units.

	Al	K1	K2	K3
$\hbar\omega_p$ (eV)	14.98	9.269	6.215	5.608
f_0	0.523	0.158	0.312	0.915
$\hbar\Gamma_0$ (eV)	0.047	0.093	2.709	0.035
f_1	0.227	0.439	0.134	0.226
$\hbar\Gamma_1$ (eV)	0.333	0.493	1.026	0.568
$\hbar\omega_1$ (eV)	0.162	0.153	1.706	0.185
f_2	0.050	0.149	1.683	1.120
$\hbar\Gamma_2$ (eV)	0.312	2.355	1.283	2.799
$\hbar\omega_2$ (eV)	1.544	2.031	1.684	1.521
f_3	0.166	0.007	1.132	0.001
$\hbar\Gamma_3$ (eV)	1.351	0.860	2.106	0.007
$\hbar\omega_3$ (eV)	1.808	2.885	2.907	2.615
f_4	0.030	0.024	0.172	0.035
$\hbar\Gamma_4$ (eV)	3.382	0.546	4.067	0.468
$\hbar\omega_4$ (eV)	3.473	1.701	0.258	1.723
f_5	0.523	0.158	6.215	5.608
$\hbar\Gamma_5$ (eV)	0.047	0.093	0.312	0.915
$\hbar\omega_5$ (eV)	0.227	9.269	2.709	0.035

CONCLUSION

The semibounded medium model suits pretty well for the RAE data of the samples of D16AT alloy irradiated by high current pulsed relativistic beams. We calculate the optical constants of the samples and obtain parameters for the dispersion Lorentz-Drude model of the samples. The birefringence of samples induced by the irradiation was supposed but not proved due to the insufficient accuracy of the available data.

Acknowledgments

This work was supported by the Simons Foundation Program: Presidential Discretionary-Ukraine Support Grants, Award No 1030287.

ORCID

Mykola O. Azarenkov, https://orcid.org/0000-0002-4019-4933; **Alexander V. Gapon,** https://orcid.org/0000-0003-4362-8060
Oleksii A. Haluza, https://orcid.org/0000-0003-3809-149X; **Volodymyr V. Lytvynenko,** https://orcid.org/0000-0003-4850-2555

REFERENCES

[1] S. Valkov, M. Ormanova, and P. Petrov, Metals, **10**, 1219 (2020). https://doi:10.3390/met10091219.
[2] Y.F. Ivanov, V.E. Gromov, D.V. Zagulyaev, S.V. Konovalov, and Yu.A. Rubannikova, Steel Transl. **52**, 71 (2022). https://doi.org/10.3103/S0967091222010120.
[3] T. Abou Elmaaty, S. Okubayashi, H. Elsisi, and E. Abouelenin, J. Polym. Res. **29**, 117 (2022). https://doi.org/10.1007/s10965-022-02952-4.
[4] G. Wang, D. Wang, and M. Huang, Food Biophysics **18**, 470 (2023). https://doi.org/10.1007/s11483-023-09787-6.
[5] V. Sonkamble, and N. Phafat, Discover Mechanical Engineering **2**, 1 (2023). https://doi.org/10.1007/s44245-022-00008-x.
[6] B. Jin, D. Zhao, F. Liang, L. Liu, D. Liu, P. Wang, and M. Qiu, AAAS Research, Article ID 9797058 (2021). https://doi.org/10.34133/2021/9797058.
[7] K.A. Osintsev, V.E. Gromov, S.V. Vorob'ev, Yu.F. Ivanov, and I.A. Panchenko, Steel Transl. **52**, 375 (2022). https://doi.org/10.3103/S0967091222040106.
[8] W.B. Liao, Z.Y. Liu, M.J. He, C. Feng, F. Wang, and J. Huang, J. Therm. Spray. Tech. **30**, 2128 (2021). https://doi.org/10.1007/s11666-021-01281-0.
[9] J. Kim, D.M. Chun, H.W. Park, and J. Kim, Int. J. of Precis. Eng. and Manuf.-Green Tech. **10**, 71 (2023). https://doi.org/10.1007/s40684-022-00420-4.
[10] A.I. Belyaeva, A.A. Galuza, V.F. Klepikov, V.V. Litvinenko, A.G. Ponomarev, M.A. Sagajdachny, K.A. Slatin, et al., PAST, **2**(93), 191 (2009). https://vant.kipt.kharkov.ua/ARTICLE/VANT_2009_2/article_2009_2_191.pdf
[11] A.D. Rakic, A.B. Djurisic, J.M. Elazar, and M.L. Majewski, Appl. Opt. **37**(22), 5271-83 (1998). https://doi.org/10.1364/ao.37.005271
[12] H. Fujiwara, *Spectroscopic Ellipsometry: Principles and Applications* (Wiley, 2007), p 369.
[13] S.E. Donets, V.V. Litvinenko, Yu. B. Poltoratskiy, A.G. Ponomarev, and V.T. Uvarov, East Eur. J. Ent. Tech. **4/5(52)**, 14 (2011). https://journals.uran.ua/eejet/article/view/1398/1296
[14] V.V. Bryukhovetsky, V.V. Lytvynenko, D.E. Myla, Yu. F. Lonin, A.G. Ponomarev and V.T. Uvarov, J. Nano. Electr. Phys. **13**, 06025 (2021). https://doi.org/10.21272/jnep.13(6).06025
[15] V.V. Arsenyuk, M.I. Bazaleev, S.E. Donets, V.F. Klepikov, V.V. Lytvynenko, Yu.B. Poltoratskiy, A.G. Ponomarev, et al., PAST, **6(91)**, 124 (2007), https://vant.kipt.kharkov.ua/ARTICLE/VANT_2007_6/article_2007_6_124.pdf

ОПТИЧНІ ПАРАМЕТРИ ЗРАЗКІВ АЛЮМІНІЄВОГО СПЛАВУ, ОПРОМІНЕНИХ СИЛЬНОСТРУМНИМИ РЕЛЯТИВІСТСЬКИМИ ЕЛЕКТРОННИМИ ПУЧКАМИ

Микола О. Азаренков[a,c], Олексій А. Галуза[b], Олександр В. Гапон[b], Володимир В. Литвиненко[d]

[a] Національний науковий центр «Харківський фізико-технічний інститут» вул. Академічна, 1, Харків, 61108, Україна
[b] Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, Харків, 61002, Україна
[c] Харківський національний університет імені В.Н. Каразіна, м. Свободи, 4, Харків, 61020, Україна
[d] Інститут Електрофізики та Радіаційних технологій НАН України, вул. Чернишевська, 28, 61002, Харків, Україна

Алюмінієві сплави Д16, Д16АТ широко використовуються як конструкційні матеріали в авіабудуванні. Питання, пов'язані з покращенням властивостей елементів конструкцій зі сплавів шляхом модифікації поверхні, зараз викликають великий інтерес. Об'єктами дослідження в нашій роботі є зразки алюмінієвого сплаву Д16АТ, опромінені сильнострумовими релятивістськими електронними пучками. Залишаючи осторонь матеріалознавчі аспекти, у цій роботі ми зосередилися на моделюванні оптичних властивостей зразків. Актуальність проблеми пов'язана з тим, що оптичні методи аналізу поверхні набули широкого поширення завдяки своїй універсальності та ефективності. Завдяки обробці попередньо виміряних даних еліпсометрії ми отримуємо оптичні константи зразків та їх дисперсію у видимій області довжин хвиль. Використаний метод полягає в апроксимації коефіцієнта відбиття, розрахованого з даних еліпсометії шляхом знаходження значень параметрів у моделі методом найменших квадратів. Вважається, що коефіцієнт відбиття відповідає напівобмеженому одновісному середовищу з оптичною віссю, перпендикулярною межі розділу середовища з однорідним і діелектричним навколишнім середовищем. Діелектрична функція напівобмеженого середовища апроксимується моделлю Друде-Лоренца. Обговорюється можливість подвійного променезаломлення зразків, викликаного опроміненням електронними променями.

Ключові слова: *електронно-променева обробка; алюмінієвий сплав; оптика металів; еліпсометрія*