

Dynamics of combined electron beam and laser dispersion of polymers in vacuum

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Abstract. The mechanisms of the impact of the laser assisting effect on the dispersion kinetics and on the structure of the deposited layers in electron beam dispersion of a polymer target were analyzed. The proposed model and analytical expressions adequately describe the kinetic dependence of the polymer materials dispersion rate in a vacuum on the intensity of laser processing of their dispersion zone.

1. Introduction

When a flow of charged particles (ions, electrons) impact on the surface of the polymer material in order to generate the active gas phase, complex physicochemical processes proceed, the character and the kinetics of which are determined, first of all, by the particles energy, the nature of the polymer, which ultimately affects the structure and composition of volatile dispersion products, their reaction activity and, accordingly, the structure and properties of the polymerized layers [1]. Further impact on the dispersion zone of the electromagnetic radiation allows expecting significant changes in the mechanism and the kinetics of those processes.

The impact of the assisting radiation on the polymer dispersion processes is multifactorial; it depends on the target nature and the radiation parameters [2–4]. It is manifested, first of all, in additional heat activation of macromolecules, bond breakage (if the photon energy is higher than the binding energy), photochemical activation of the formed volatile dispersion products and, accordingly, increase in their reactivity. Short-wave electromagnetic radiation may also cause photoelectron emission, which reduces the value of the electric charge adsorbed when processed by electrons and, accordingly, determines a decrease in intensity of the electric field decelerating the incident electron flow. This, in turn, increases the particles energy and, accordingly, the dispersion intensity, determines higher secondary electronic emission that affects the character and the kinetics of the secondary polymerization process.

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2. The physical model

The quantitative analysis of patterns of the material laser dispersion is based on a comparison of the photon energy $\varepsilon = hc/\lambda$ (where h is the Planck constant, c is the speed of light, λ is the wave-length of laser radiation) with the binding energy of the atoms. When the materials are evaporated by laser pulse emission, the change in state of the target material is significantly determined by the absorption intensity of the energy by the material, which is in simple case described by Beer-Lambert law

$$I(x, y, z) = I_0(x, y)e^{-\alpha z}, \quad (1)$$

where I_0 is the intensity of the light that falls on the target surface; α is the absorption coefficient that depends on the nature of the material and the radiation wave-length; z is the radiation penetration depth.

The absorption intensity significantly determines the temperature condition of the process. And if the photon energy is high enough then the electron excitation caused by the photon absorption may lead to direct photochemical decomposition. If the radiation quantum energy is lower than the atoms binding energy and the heat flow density exceeds a certain threshold then the main dispersion mechanism is the thermochemical decomposition [5].

As noted, when the electron flow is exposed on the target surface, its charging occurs due to the introduction of the particles into the polymer by fixing them on traps in the surface layer. The analysis of the electrophysical processes that occur when dispersing the polymers shows that the electrostatic charge value on the surface is determined by the electrons density j , the secondary electron emission coefficient α , and, when volatile macromolecules fragments are formed, their ionization coefficient β . Note that the secondary emission coefficient α significantly depends on the energy W of the particles bombarding the surface. At sufficiently low electron energies, it has, as a rule, the value greater than one. It is known, for example, that when the surface of PTFE (polytetrafluorethylene) is irradiated by electron flow, its charging is observed at the energy $W > 1.5$ keV. At $W < 1.5$ keV, the secondary electron emission coefficient α is greater than one and the surface charging does not occur. When short-wave electromagnetic radiation with the photon energy $\varepsilon = h\nu > A_e$ (where A_e is electron work function) is exposed to the dispersing zone, the electron emission occurs with the flux density $J_f = J/h\nu$ (where J is the electromagnetic radiation energy flux density).

Given these factors and assuming that the electrical conductivity of the polymer is low enough, the charge surface density q change in time may be described by the following system of differential equations

$$\begin{cases} \frac{dq}{dt} = j - \alpha j + \beta \frac{dm}{dt} - eJ_f \\ \frac{dm}{dt} = -kUj \end{cases}, \quad (2)$$

where m is the mass of the polymer target; k is the value that depends on the polymer nature; $U = W/e$ is the effective accelerating voltage of the electron gun that disperse the polymer target; W is the electrons energy; e is the electron charge.

As already noted, the secondary electronic emission coefficient depends on the electron energy (or the accelerating voltage U) also in linear approximation, which can be calculated from the correlation

$$\alpha = \alpha_0 - dU, \quad (3)$$

where α_0 and d are constant values for this polymer.

In (2), we note that, according to the experimental data [6], the volatile products generation rate (the dispersion rate $V_d = \frac{dm}{dt}$) is proportional to the power of energy deposition on the target.

The appearance of charge on the surface determines the existence of an electric field decelerating

the incident electrons. Then the effective acceleration voltage is

$$U = U_a - \frac{\alpha}{C}, \quad (4)$$

where U_a is the acceleration voltage of the electrons (ions) source; C is the capacitance of the charged polymer layer.

Differentiating (4), we obtain

$$\frac{dq}{dt} = -C \frac{dU}{dt} \quad (5)$$

Then, based on (2) and taking into account (3) and (5), we have

$$\frac{dU}{dt} = -\frac{1}{C} \{ [1 - \alpha_0 + (d + k\beta)U] j - eJ_f \}. \quad (6)$$

After integration of (6) with the initial condition $U(0) = U_a$, the effective voltage expression is as follows

$$U = \frac{j(\alpha - 1) + eJ_f}{j(d + k\beta)} + \left[U_a - \frac{j(\alpha - 1) + eJ_f}{j(d + k\beta)} \right] \exp\left(-\frac{d + k\beta}{e} jt \right). \quad (7)$$

One should note that the value of $U_0 = \frac{j(\alpha - 1) + eJ_f}{j(d + k\beta)}$ is numerically equal to the electron source acceleration voltage whereby the dispersing process is stationary and the charge accumulation on the polymer surface does not occur.

The analysis of (6) shows that at the lumen output $J_f = \frac{j}{e} [U_a(d + \beta k) + 1 - \alpha_0]$ there is lack of charge and the standard disperse mode is realized. If the electromagnetic radiation intensity is higher than that value then, due to the photoeffect, a positive charge appears on the surface and the induced electric field is accelerating.

The linear velocity of the dispersion is obtained from (2) with (7)

$$V_d = \frac{k}{\rho} j \left[U_0 + (U_a - U_0) e^{-\frac{t}{\tau_0}} \right], \quad (8)$$

where $\tau_0 = \frac{C}{j(d + \beta k)}$ is the charging time constant; ρ is the target material density.

It is followed from (7) and (8) that, with sufficiently large dispersion time $t \gg \tau_0$, the value of the electron gun accelerating voltage U_a virtually does not affect the energy of the particles bombarding the target and the dispersion rate. Therefore, to ensure high efficiency and stationarity of the dispersing process with such time values, the accelerating voltage of the electric gun should be set close to U_0 , and to ensure high dispersion rate, intensive enough electron (ion) flows should be used. However, it is necessary to consider that as j increases, the charging time constant decreases, the efficiency of charge removal by electromagnetic assisting decreases and the charge is accumulated faster on the surface, which reduces the effective energy of electrons and, accordingly, the dispersion rate.

The stationary value of the dispersion rate while assisting the electron beam dispersion with the electromagnetic radiation may be expressed as follows $\Delta V_{d,0} = \frac{k}{\rho} \frac{j(\alpha - 1) + eJ_f}{(d + \beta k)}$, where the value linearly increases with increase in the electron flux density. The difference in dispersion rates with and

without laser assisting $\Delta V_{d,0} = \frac{k}{\rho} \frac{eJ_f}{(d + \beta k)}$ does not depend on the electron flux density but is determined only by intensity of the electromagnetic radiation.

The above kinetic features were considered in technological processes of forming composite film structures during deposition from the active gas phase with the selection of the conditions and parameters of coating condensation on the substrate by pulse laser-assisted electron beam deposition of initial components [2, 3].

3. Conclusion

The analysis of the possible mechanisms of laser assisting impact on the dispersing kinetics and the structure of the deposited layers in electron beam target dispersion revealed that the main impact factors on the target are the thermal effect produced by long-wave radiation, the photochemical activation and the photo emissive effect. The latter process in electron beam dispersion affects charging of the surface layer of the polymer sputtered and finally on the energy of the electrons that bombard the target. The proposed model and analytical expressions satisfactory describe the kinetics dependence of the dispersion rate of polymer materials in a vacuum on the intensity of laser processing of their dispersion zone.

Acknowledgments

This work was supported by the Ministry of Education and Science of Russian Federation (main part, project № 1079)

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