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Degradable plasma polymer films with tailored hydrolysis behavior

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ABSTRACT

Thin films based on polylactic acid have been prepared using plasma-assisted vacuum thermal deposition under varying RF glow discharge power and characterized in terms of chemical composition and structural homogeneity. As a measure of the degradability of the films their wash-off and hydrolysis behavior were monitored. The properties of the films were found to be tunable to a significant degree by the deposition conditions.

1. Introduction

A special subtype of polymers are materials that are degradable and/ or biodegradable, like polyethylene oxide and polylactic acid. These polymers have important applications in the biomedical field [1-5] as well as for packaging, food industry or medicine [6-10]. In the case of polylactic acid, mechanism of biodegradation is based on hydrolysis of ester bonds in the polymer. Degradation can proceed from the surface as well as from the volume of the polymer [11].

Polylactic acid is typically synthesized by polycondensation of lactic acid [12]. Low-temperature plasma polymerization was found to be effective for fabrication of thin polymer-like coatings [13-21] including ester-containing films based on ethyl lactate [22-25].

Typically, polymers prepared using classical “wet chemistry” methods have well-ordered chemical structure. However, classical methods of synthesis are often limited in the degree of crosslinking that can be obtained in biodegradable polymers without residues of the crosslinking agent. On the contrary, plasma-based methods typically produce easily very highly crosslinked structures, but the molecular structure of the material is typically close to being random.

Plasma-assisted vacuum thermal deposition (PAVTD) is a technique based on low pressure thermal decomposition of powder of a “source” classical polymer (“precursor”) [21-30]. Oligomers released from the precursor serve then as “monomers” for plasma polymerization. In this way, it is possible to produce plasma polymers that bridge the limits of classical polymers and plasma polymers [31,32]. In

this way various properties of the films can be controlled, including those based on PLA [33,34]. This study was focused mainly on covering a broader range of deposition conditions.

2. Experimental

2.1. Deposition of plasma polymer

The general setup of the experiment was described e.g. in Ref. [31] with the difference that glow discharge electrode with grounded shielding was used instead of magnetron. The RF (13.56 MHz, 0 W or 2-100 W) electrode with the diameter 81 mm covered with a glass target was 6 cm below a heated crucible with 200 mg of powdered solid polymer precursor ("source" polymer). The substrates (single-side polished silicon wafers, gold-coated silicon, glass slides) were placed 15 cm above the crucible on a grounded holder. During the experiment, the crucible was heated to 240 °C. PLA (molar mass $m_w = 10000-20000 \text{ g. mol}^{-1}$) prepared by polycondensation according to Ref. [6] was used as a source polymer for the process [35,36]. Argon under the pressure of 4 Pa (flow rate of 8 sccm, $2.4 \times 10^{-7} \text{ kg.s}^{-1}$) was used to ignite the plasma. The deposition rate was monitored by quartz-crystal microbalance sensor. Deposition rate was typically from 10 nm.min^{-1} to 40 nm. min^{-1} . However, the deposition rate was kept within 30% variance during the deposition of one sample.

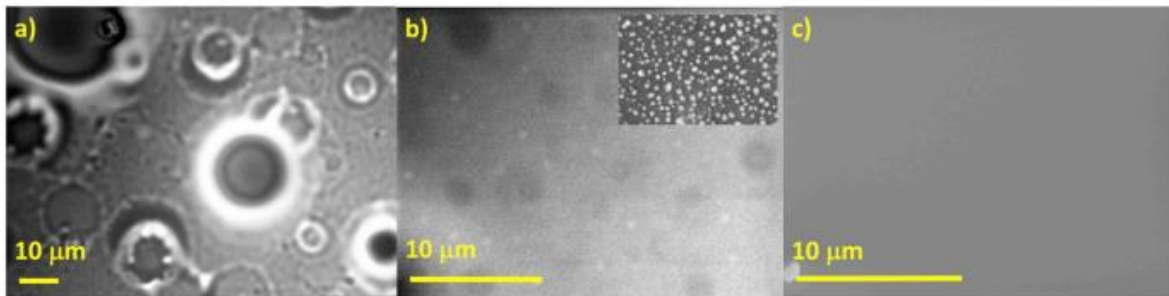


Fig. 1. SEM micrographs (acceleration voltage 2 kV, working distance 6.3 mm) of PLA-like films. Various effective plasma powers have been compared: a) 0.54 W (nm.min^{-1}) b) 2.9 W (nm.min^{-1}) and c) 26 W (nm.min^{-1}) (right). In the inset of image b) is the SEM micrograph of the sample after immersion in water and drying (in the same scale as the image b)).

Since the total deposition time per one fill of the crucible was typically 30 min (amounts to 3 or 4 samples) the mass flow of the oligomers from the crucible was typically $1 \times 10^{-7} \text{ kg.s}^{-1}$ (below 0.5 sccm considering the molar mass of the oligomers [33,34]).

As-deposited film thickness of the films established using spectroscopic ellipsometry (Woollam M2000DI) was 100-200 nm.

2.2. Scaling parameter

The deposition rate of PLA was found to be more sensitive to fluctuations of the temperature of the crucible than in the case of PEO. As a crude yet useful scaling parameter in a plasma polymerization so-called Yasuda parameter [13,14,38-42].

$$Y=W/(F.M) [\text{J.kg}^{-1}]$$

(where W is the plasma power in polymerization zone, F is the monomer molar flow and M is the molar mass of the monomer) has been established.

In classical plasma polymerization from the gas phase using low-molar mass monomers, the monomers typically do not stick well to the substrate. They do not contribute to the deposition rate unless they are activated in the plasma (transformed mostly into radicals). The Yasuda parameter then generally corresponds to the deposition rate of the film and can be used also as the scaling parameter for studying the properties of the films in dependence on the deposition conditions.

In the case of PAVTD technique, the “monomers” are actually long ($\sim 1000 \text{ g.mol}^{-1}$) oligomers that stick well to adjacent surfaces even without plasma activation and the deposition rate is then nearly independent on the plasma power. The deposition rate is then actually a good measure of the momentary mass flow of the monomer. Therefore, we adopt a scaling factor of (relative) effective plasma power in the form

$$P_{\text{eff,rel}} = W / (dh/dt) \text{ [W.min.nm}^{-1}\text{]}$$

Where dh/dt is the deposition rate. However, this parameter does not correspond to the deposition rate (as Yasuda parameter under optimal conditions does). It is to be used only for comparison of the properties of the films prepared at various deposition rates and plasma powers.

The exact proportion of total plasma power devoted to plasma polymerization is hard to quantify. In the particular setup, the spreading of the discharge did not observably change with increasing RF power, so we take the proportion of power devoted to plasma polymerization as roughly constant. The influence of the discharge (ion bombardment, UV photons) on the surface of the films is considered to be negligible.

It shall be noted that absolute values of effective plasma power are valid only for a particular experimental setup.

2.3. Determination of film structure and composition

The deposited films have been also characterized with regard to their structures. The analysis has been done using high-resolution scanning electron microscopy (HR-SEM, JSM7500F by JEOL) with a field-emission gun and secondary electron in-lens detector (maximum resolution of 1.0 nm at 15 keV). The SEM device can operate without preparative conductive coatings. The elemental composition of the films in dry state was analyzed by x-ray photoelectron spectroscopy (XPS, Phoibos 100, Specs). Infrared spectra of the films were obtained using reflection-absorption setup (FTIR-RAS, Bruker Equinox 55) for samples on gold-precoated substrates.

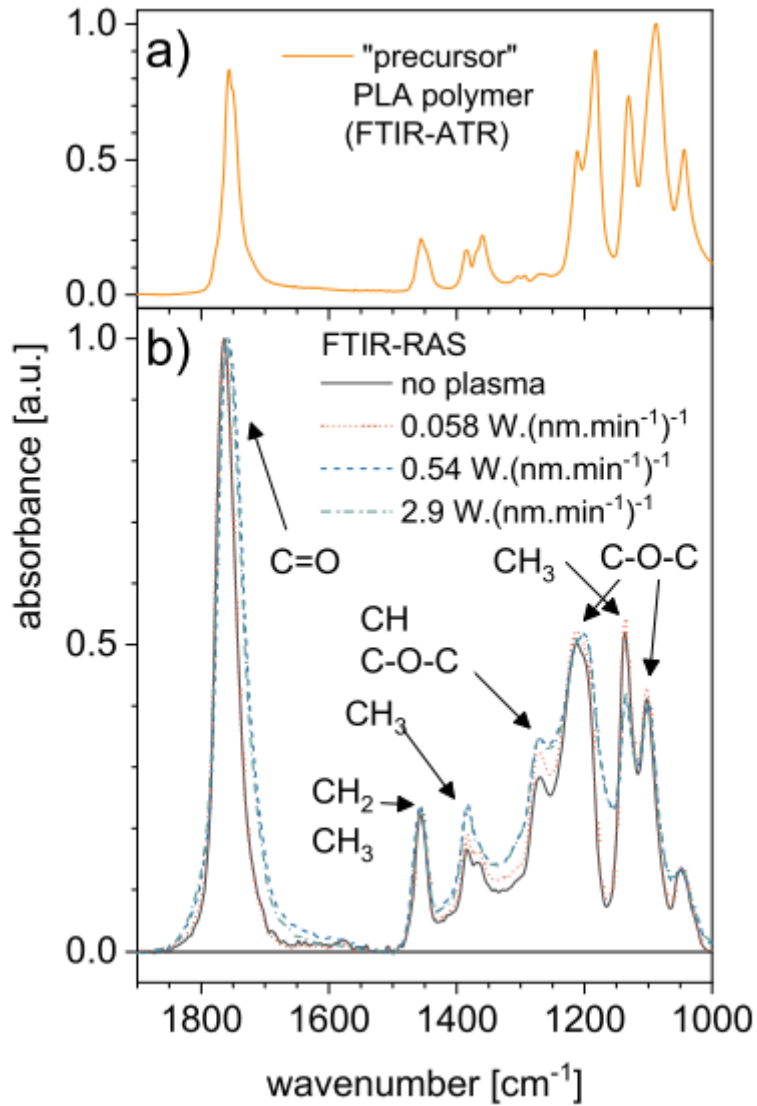


Fig. 2. Infrared spectra of the a) PLA "precursor" [34] and b) of the PAVTD-prepared PLA-like thin films prepared at varying effective plasma power.

2.4. Wettability measurements

The wettability of the PLA films prepared at different plasma power was analyzed using the static water contact angle measured on the Surface Energy Evaluation system (See System E, Advex instruments s.r. o., Brno, Czech Republic). The drops of distilled water (3 μl in volume) were put on different sites of each film sample, the contact angle was then evaluated as the average of three measurements and standard deviation (which was up to 10% of mean value in all cases).

2.5. Characterization of hydrolysis

The physical thickness of the film during hydrolysis has been characterized in situ in water using spectroscopic ellipsometry (Woollam M2000DI) with a liquid cell. Chromatographic separation was carried out at the column oven temperature $40\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ with a flow rate 1.0 mL/min of isocratic elution using two solvents: A - (0.03 mol/l H_3PO_4 in water) and B - acetonitrile HPLC grade in ratio 88:12 v/v. The injected sample volume was 20 μl . The quantitation wavelength was set at 200 nm.

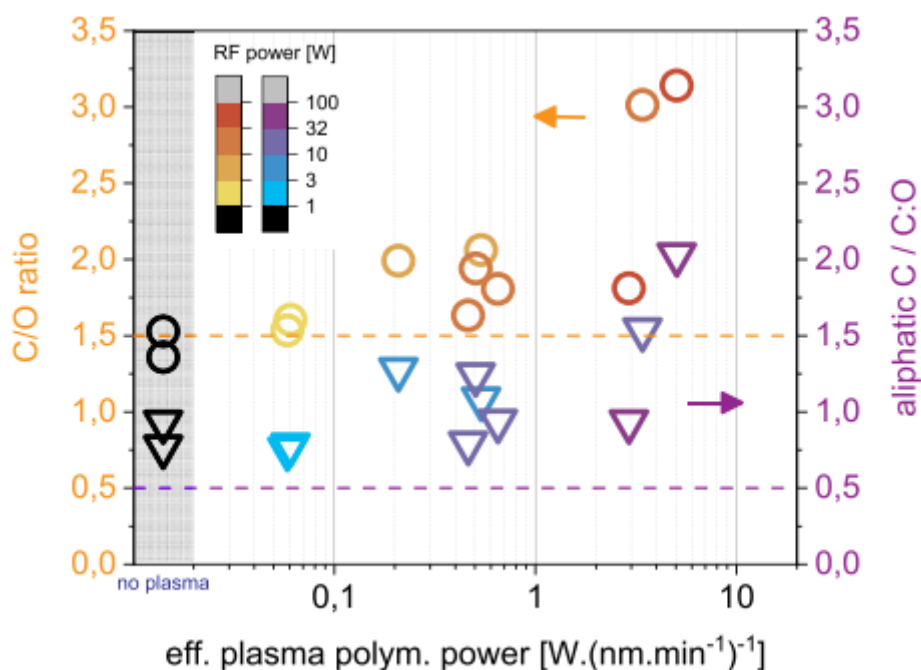


Fig. 3. Chemical composition of the PLA-like films measured using XPS. Carbon/oxygen elemental ratio and the ratio of number of carbon atoms unbound/bonded to oxygen for varying effective plasma power are shown. The symbols are color-coded to show also the RF power alone. Dashed lines denote these ratios for bulk PLA. The values of these ratios for the films prepared without plasma are placed arbitrarily. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results and discussion

In terms of surface morphology, SEM reveals a lateral structure of deposited films depending on the deposition power (Fig. 1). At low effective plasma power ($0.54\text{ W (nm}\cdot\text{min}^{-1})^{-1}$) droplet structures (up to over $10\text{ }\mu\text{m}$ in diameter) dominate the surface. Larger droplets disappear at higher plasma powers and the surfaces exhibit no vertical variations of the topography (as seen by the side SE detector). However, at medium effective plasma power ($2.9\text{ W (nm}\cdot\text{min}^{-1})^{-1}$), a fine lateral texture (smaller than $3\text{ }\mu\text{m}$) appears indicating variations of material density rather than topographic features. At the highest effective plasma power ($26\text{ W (nm}\cdot\text{min}^{-1})^{-1}$) smooth homogeneous films are produced. The lateral features on the surface of the films can be connected to the island or particulate-like structures that remain on the surface after immersion in water (see below).

Infrared spectra of the films (Fig. 2) show that most of the chemical structure of the original polymer [34,37] is well preserved. As expected, slight broadening of the peaks indicates some fragmentation of the original polymer. With increasing power in the discharge, CH_x-containing groups' (especially -CH₃)

content is increasing. These changes occurred already in the films prepared at low effective plasma powers ($<0.5 \text{ W (nm}\cdot\text{min}^{-1})^{-1}$).

The chemical composition of the films obtained using XPS (Fig. 3) shows a similar trend. The films prepared without the plasma reproduce the C/O elemental ratio of PLA well. Films prepared with plasma on show an increase of this ratio. Moreover, a more detailed analysis of the C1s carbon peak shows that in the films prepared with plasma power on, carbon is more preferentially bound (up to 75%) in aliphatic bonds while in the original PLA, 2/3 of carbon atoms are bound to oxygen.

Simultaneously, analysis of the oxygen peak shows that with increasing plasma power the ether C-O-C bond disappears and oxygen remains bound in the more stable carbonyl C=O group.

Wettability was analyzed using the sessile droplet method. The measured contact angles for water increased with increasing effective plasma power, ranging from 40 to 70° depending on the conditions of plasma deposition. Wettability of the films decreases with increasing relative power, as can be expected when more polar oxygen-containing groups are replaced with less polar C:H groups.

The films were tested for stability during short-term (2 h) immersion in water (Fig. 4). The relative thickness loss after immersion into water and subsequent drying was found to be the highest for the films prepared at low effective plasma power (Fig. 4a), where nearly 99% of the film material has been lost during immersion. On the contrary, films prepared at the highest effective power were found to be much more stable and exhibited only minor thickness loss. The short-term thickness loss can be in principle caused both by washing-off of the low-mass fragments off the films as well as by hydrolysis. Film thickness measurements do not actually measure the rate of hydrolysis - they only show how much of the material has been released (in any form, hydrolyzed or not) into water and subsequently removed with it. The situation can be further complicated by the structure of the films (Fig. 1). It appears that in the bottom layer of the film some more stable - presumably more crosslinked - domains are formed and those domains resist the wash-off. Those features can be actually the initial stages of the film growth as reported for PAVTD of polyethylene [43].

Since the RF powers used in the experiments differed up to 1:50 and the deposition rates differed less than 1:5, the dependency of the thickness loss on the RF power (Fig. 4b) looks qualitatively similar like the dependency on the effective plasma power. However, the influence of the deposition rate (Fig. 4c and d) is not negligible. This makes the effective plasma power better scaling factor of the film properties than the RF power alone.

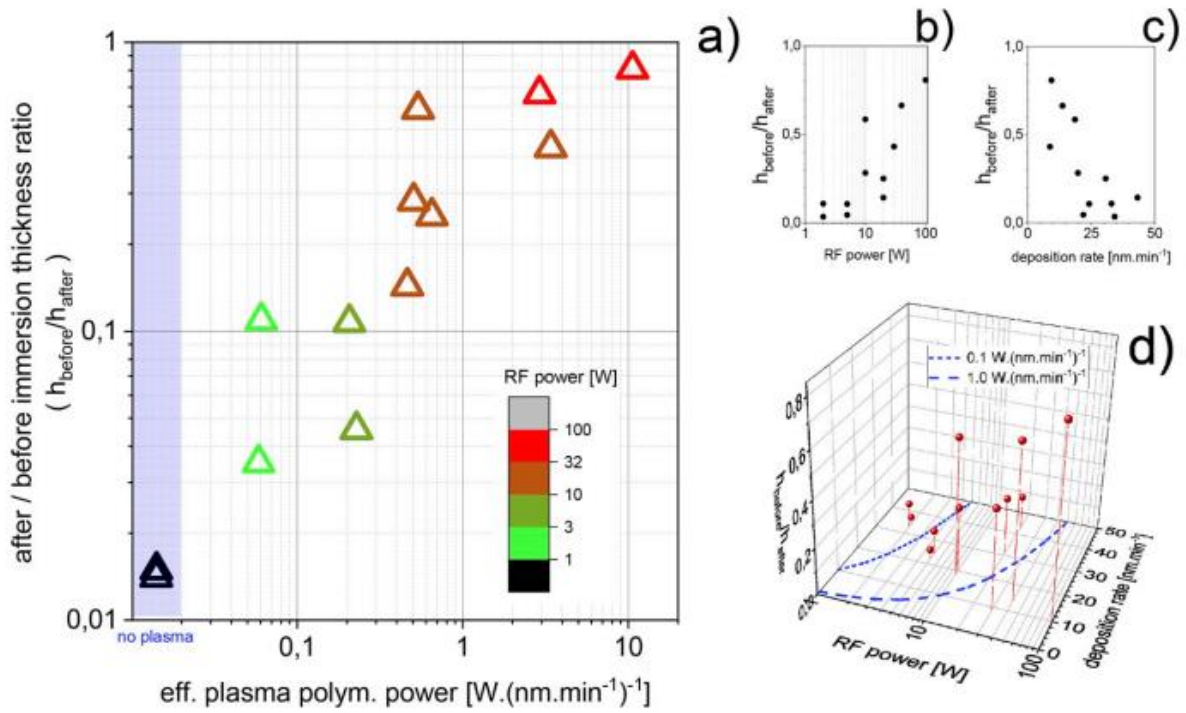


Fig. 4. The ratio of thickness of dry PLA-like films before and after 2 h of immersion into water measured using ellipsometry. a) Dependence on varying effective plasma power. The symbols are color-coded to show also the RF power alone. The values of this ratio for the films prepared without plasma are placed arbitrarily. b) Dependence on RF power. c) Dependence on the deposition rate. d) 3D graph summarizing the graphs a), b) and c). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

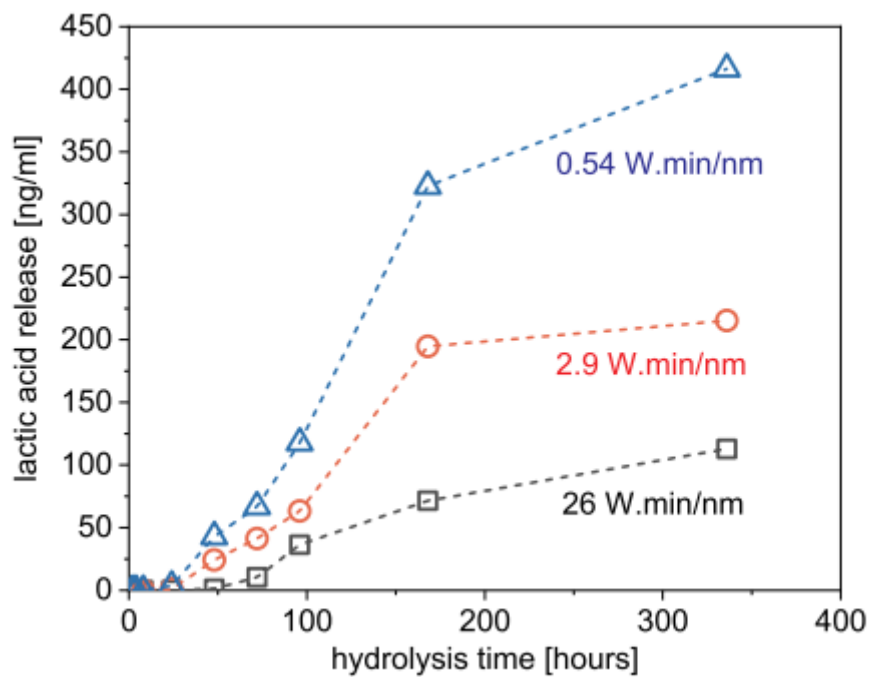


Fig. 5. Hydrolysis of PLA-like films prepared at varying effective plasma power characterized by HPLC-UV.

The hydrolysis characterized by HPLC-UV detected as the contents of lactic acid released into water (Fig. 5) shows much slower decay of the material of the films than the measurements of thickness, proceeding on the timescale of days to weeks. Since this was a continuous experiment, the measured lactic acid release is a sum of products of hydrolysis of the material bound to the substrate and of the material washed-off into water.

The values of lactide release were almost negligible within initial 48 h, after which a continuous increase occurred until the maximum tested time period (two weeks). Films prepared at lower effective power produce a higher amount of lactide fragments and a higher amount of lactic acid (hydrolysis is more rapid than in the case of films prepared at high effective power). However, the timescales of lactic acid release do not depend significantly on the effective power used during the preparation of the films.

Characterization of hydrolysis in combination with the short-term thickness loss measured by ellipsometry, together with the chemical structure analysis shows that at least significant parts of PLA-like chain are well preserved in all films. In the films prepared at low effective plasma power, the chains are only weakly bound together and they are easily washed off during swelling in water. Films prepared at higher power appear to be much more crosslinked and more C:H-like, but the PLA-like structure is still present. Films prepared at high effective plasma power ($>1 \text{ W (nm}\cdot\text{min}^{-1})^{-1}$) still undergo hydrolysis in water but with a slower rate.

4. Conclusions

PLA-like films were prepared using PAVTD. The films were found to well correspond to the original PLA polymer in terms of the chemical structure. In the films prepared at higher plasma power, oxygen content (esp. in ether groups) decreased. The control of degradability of the films through deposition conditions was demonstrated. Films prepared at higher effective plasma power exhibited lower mass loss after immersion and slower hydrolysis.

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