

IMPORTANCE AND NECESSITY OF THE SURFACE MODIFICATION OF NYLON 6 FILMS FOR FUTURE BIOMEDICAL APPLICATION

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Abstract

Polyamide plays an important role in biomedical application such as suture material, coated textile against skin infection, wound dressing, catheters and bone tissue scaffolds. Surface modification of polyamide is very crucial factor to improve its performances by imparting desirable biomaterial properties. This report is focused on the efficient reduction of amide functional groups to secondary amine on Nylon 6 film surface with borane-tetrahydrofuran (BH₃-THF) complex, followed by further alkylation. More precisely, we have studied the reaction of benzyl chloride (C₆H₅CH₂Cl) in presence of potassium *tert*-butoxide (*t*-BuOK) on the modified Nylon 6 films. Thus, introduction of benzyl group to secondary amine of modified Nylon 6 has been accomplished. This type of transformation is expected to be generally applicable for functionalization of almost any polyamide. By using different alkylation reactions we will be able to tune the surface properties of polymers obtained for almost any applications. We also hope that polymers thus obtained will be biocompatible. The surface modifications were confirmed by both non-spectral methods and spectroscopic as well as microscopic analyses. Water contact angle (WCA) and free surface energy (FSE) measurements indicated the significant change in surface morphology that were established by X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared spectroscopy (FT-IR), Raman spectroscopy and atomic force microscopy (AFM). We are firmly convinced of the future prospect for further surface modification of these functionalized nylon 6 films with high potential in the field of biomedical application.

Keywords: Biomedical application, surface modification, polyamide, biocompatibility

1. INTRODUCTION

Nylon 6, a polyamide, is a commercialized polymer that is widely used in biomedical applications because of its strength, flexibility, toughness and biocompatibility [1]. Polyamides in the form of suture materials, coated textiles against skin infection, wound dressings, catheters and bone tissue scaffolds are well known on a global scale [2-4]. Chemistry of polymer surface plays an important role and further modification of polymer by introducing specific functional groups on the surface improves its performance. Since nylon membranes comprise negligible concentration of terminal amino groups, activation of amide groups should allow more homogenous distribution of activated groups on the surface of nylon [5]. Nylon surfaces are modified by either physical or chemical methods. The first category includes mainly the treatment with UV radiation and plasma. Lack of the formation of well-designed surface is one among the limitations when employing physical methods. A more efficient modification approach is application of chemical methods by reaction at the amide groups through hydrolysis, O-alkylation and N-alkylation [1].

This research article is focused on the efficient reduction of amide functional groups to secondary amine on the surface of Nylon 6 film by borane-tetrahydrofuran (BH₃-THF) complex [6], followed by further alkylation. More precisely, we have studied the reaction of benzyl chloride (C₆H₅CH₂Cl) in presence of potassium *tert*-butoxide (*t*-BuOK) on the modified Nylon 6 films. Thus, introduction of benzyl group to secondary amine, available on modified Nylon 6 surface, has been accomplished as a model reaction for further future approach. We will be able to tune the surface properties of polymers by using different alkylation reactions. We expect that, the nylon 6 thus obtained will maintain biocompatibility. Water contact angle (WCA) and free surface energy (FSE) measurements indicated the significant changes in the surface morphology which were subsequently confirmed by X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared spectroscopy (FT-IR), Raman spectroscopy and atomic force microscopy (AFM).

2. EXPERIMENTAL

2.1. Materials

Polyamide- nylon 6 (PA6) film, with the thickness of 0.015 mm, was supplied by Goodfellow Cambridge Ltd., (Huntingdon, England). Borane-Tetrahydrofuran complex (1 M, BH₃-THF), potassium *tert*-butoxide (*t*-BuOK), benzyl chloride (C₆H₅CH₂Cl) were obtained from Sigma-Aldrich Co., CZ. Solvents like tetrahydrofuran (99.8% THF), dimethyl sulfoxide (99% DMSO), acetone (99.5%), ethanol (96%), 2-propanol (99.8%), hexane (99.9%) and hydrochloric acid (35% HCl) were purchased from **Lach-Ner, s.r.o., CZ. All washings were performed by deionized water.**

2.2. Methods

Preparation of samples

Nylon 6 films, cut into 2 cm × 2 cm, were thoroughly rinsed with water, ethanol, 2-propanol, acetone, THF and hexane. The washed samples were dried at 50°C for 3 h under vacuum (VACUUBRAND® 10 mbar Oil-Free Diaphragm Vacuum Pump) and stored in desiccator. THF and DMSO were dried before using for carrying out the reactions.

Reduction of nylon 6 with BH₃-THF

The amide function groups of nylon 6 samples were reduced to secondary amine by following the procedure described in Herrera-Alonso *et al.* using nylon 6/6 film [6]. Dry THF (25 ml) was introduced into the Schlenk flask (250 ml) kept under argon atmosphere, containing 5 weighed dry samples with stir bar. BH₃-THF solution (4 ml, 1 M) was added at 0°C and stirred in 150 rpm. After equilibrium attained at room temperature (for an hour), the temperature was increased to 50°C and maintained for 24 h. After cooling down to room temperature, the reduced samples were washed with THF, 1 M HCl, distilled water, THF, ethanol, acetone and hexane in sonicating bath. The samples were dried at 50°C for 3 h in vacuum and stored in desiccator until next modification. The samples with reduced surface have been referred as nylon 6-NH.

N-alkylation with C₆H₅CH₂Cl

t-BuOK (0.0561 g, 0.5 mmol) was introduced into the Schlenk flask (250 ml) kept under argon atmosphere containing 5 weighed nylon 6-NH samples and stir bar. Dry DMSO (20 ml) was added into the flask and stirred at 150 rpm for 1 h, at room temperature. Subsequently, the solution containing dry DMSO (10 ml) and C₆H₅CH₂Cl (0.115 ml, 1 mmol), premixed and equilibrated at room temperature for an hour, was added via syringe into the reaction mixture. The reaction was allowed to occur for 1 h and 3 h respectively. The modified samples were rinsed thoroughly in the sonicating bath with DMSO, water, ethanol, THF, acetone and hexane; then dried at 50°C for 3 h in vacuum and stored in desiccator. Thus modified samples have been referred as nylon 6-NCH₂Ph.

Surface Characterization

The WCAs and FSEs (Kwok-Neumann model) were measured using a portable computer-based instrument with special purpose software following ISO 27448:2009 test method (See System E, Advex Instruments, CZ). WCA measurement is one of the rapid, easy and useful surface analytical techniques. The $\theta/2$ method was used to analyse the profile of sessile drop, assuming the liquid drop to be part of a sphere. WCA values were calculated from the equation (1),

$$\tan(\theta/2) = h/x \quad (1)$$

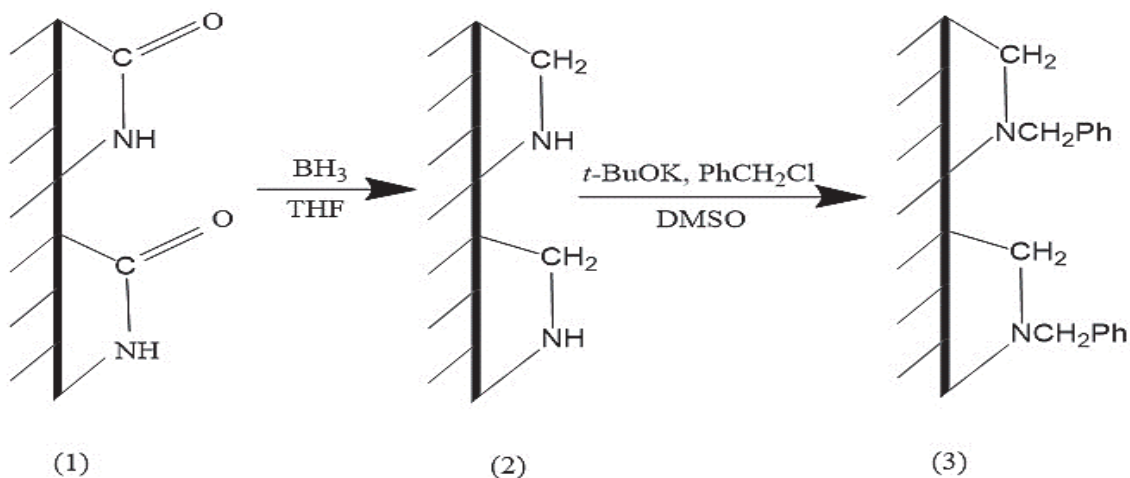
where θ = static contact angle, h = droplet height and x = half of the droplet width [7]. Contact angle measurements were performed by vertically dispensing 20 droplets (3.5 μ l/droplet) of deionised water on each sample. The mean values were taken for plotting the WCA histograms; all the values for each sample were in a range of $\pm 3^\circ$. The FSEs of the mean values of WCAs were directly measured by the software.

X-ray Photoelectron Spectroscopic (XPS) measurements were done by a Thermo Scientific K-Alpha X-ray Photoelectron Spectrometer (Thermo Fisher Scientific) using a monochromatic Al K_α radiation ($h\nu = 1486.6$ eV). The Nicolet[™] iS[™]10 FT-IR Spectrometer (Thermo Scientific[™], USA) and the DXR[™] Raman Spectrometer (Thermo Scientific[™], USA) were used to examine the changes in surface composition after the modifications of nylon 6 to nylon 6-NH and nylon 6-NCH₂Ph respectively, using wet chemistry method. The topography of the unmodified and modified nylon 6 films was studied in the air at atmospheric pressure with NanoWizard[®] 3 NanoScience AFM (JPK Instruments, Germany). Scans of the samples and subsequent evaluation of the surface roughness (R_a) were always conducted on surface areas of 10x10 μ m and 1x1 μ m. Measured data were processed using the freeware softwares Gwyddion and JPK Data Processing.

3. RESULTS AND DISCUSSION

3.1. Modification of Nylon 6 surface

The reduction reaction of amide functional groups on Nylon 6 film surfaces to secondary amine (nylon 6-NH) using borane-tetrahydrofuran (BH₃-THF) complex, followed by further N-alkylation reaction of nylon 6-NH with benzyl chloride (C₆H₅CH₂Cl) in presence of potassium *tert*-butoxide (*t*-BuOK) forming nylon 6-NCH₂Ph are shown below (Scheme 1).



Scheme 1 The schematic representation of Nylon 6 film surface modification; unmodified nylon 6 (1), nylon 6-NH (2), nylon 6-NCH₂Ph (3)

3.2. WCAs and FSEs

The WCAs measurement of the unmodified and modified films is presented in **Figure 1a**. The significant increase of mean WCAs by 11° after modification of nylon 6 films to nylon 6-NH was the indication of surface composition alteration by $\text{BH}_3\text{-THF}$. Further modification of nylon 6-NH to nylon 6-NCH₂Ph again increased mean WCAs by 11° and 12° for 1 h and 3 h reactions respectively.

The FSEs decreased consecutively after surface modifications of nylon 6, as the mean WCAs increased for consecutive reactions. The FSE values before and after modification of nylon 6 are shown in **Figure 1b**.

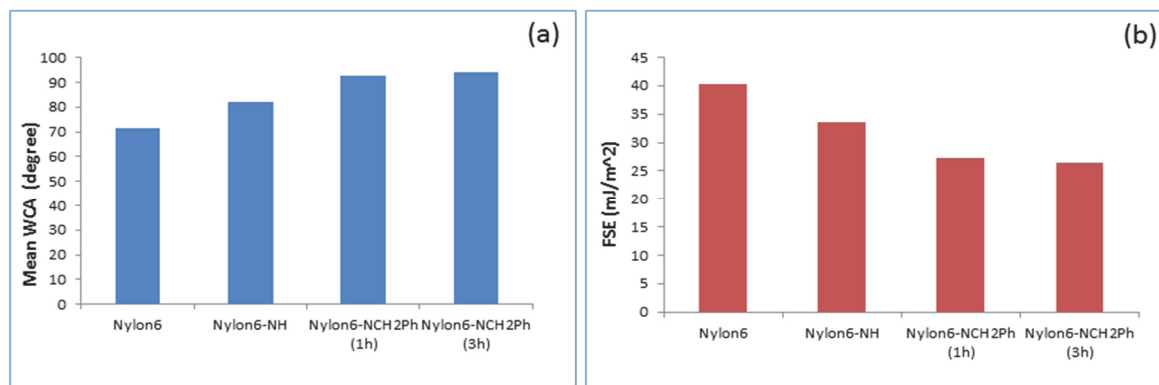


Figure 1 Surface modification of Nylon 6: WCA data (a), FSE data (b)

3.3. XPS analysis

The shifting of the binding energy of high resolution C_{1s} and N_{1s} spectra, comparing nylon 6 and nylon 6-NH (**Figures 2a, 3b**), clearly indicates the reduction of amide functional groups on nylon 6 surface to amines after modification with $\text{BH}_3\text{-THF}$. The introduction of benzyl group by N-alkylation of nylon 6-NH forming nylon 6-NCH₂Ph with benzyl chloride after 1 h and 3 h reactions was significant and was confirmed by the increase in binding energy of C_{1s} spectra and by the changed pattern of N_{1s} spectra (**Figures 2c, 3d**).

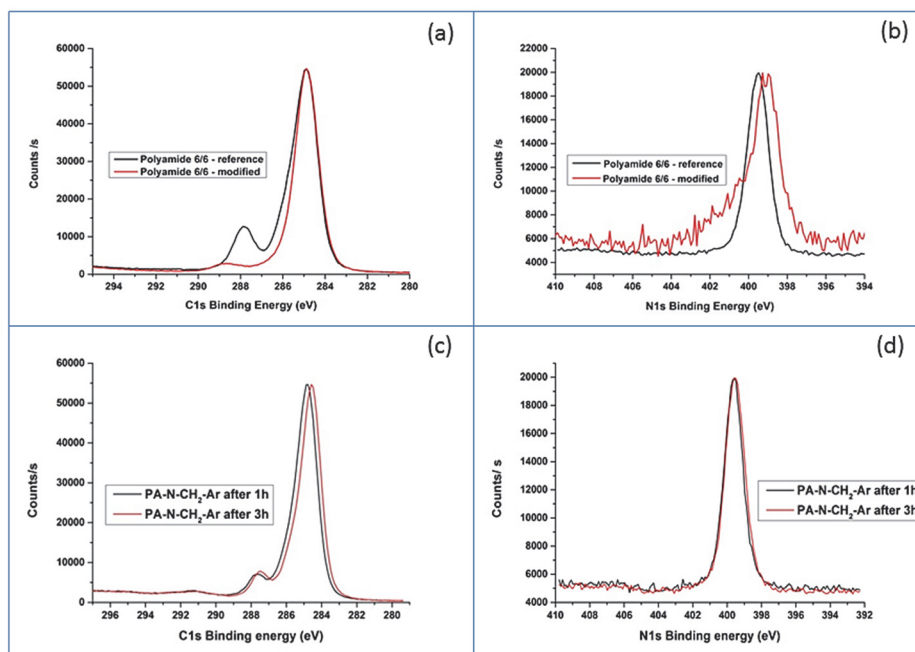


Figure 2 Surface modification of nylon 6 to nylon 6-NH: C_{1s} spectra (a), N_{1s} spectra (b); introduction of benzyl groups by 1 h and 3 h reactions forming nylon 6-NCH₂Ph: C_{1s} spectra (c), N_{1s} spectra (d)

3.4. FT-IR and Raman spectroscopy analyses

Figure 4a shows the comparison between the FT-IR spectra of nylon 6 and modified nylon 6-NH films. The characteristic vibrations of amide group (ν_{CONH_2} 1636 cm^{-1} and 1541 cm^{-1}) and the aliphatic groups (ν_{CH_2} 2854 cm^{-1} and 2926 cm^{-1}) of nylon 6 are visible for both samples before and after the reaction with BH_3 -THF. There is a new band appears at 2382 cm^{-1} corresponding to imine groups introduced via chemical treatment, indicating the step towards reduction of amide to amine. Moreover, the increase in intensity of aliphatic band stretching vibration confirms the conversion of amide to amine due to the reduction reaction of nylon 6 films. The modification of nylon 6-NH by introduction of benzyl group forming nylon 6-NCH₂Ph film could not be detected by FT-IR due to the sensitivity limitation. Therefore, the surface composition changes were studied by Raman spectroscopy. **Figure 4b** shows the strong Raman shift at 2870-3100 cm^{-1} for nylon 6-NCH₂Ph films, obtained by both 1 h and 3 h reactions of nylon 6-NH with benzyl chloride, although the Raman intensity is higher for 3 h reaction confirming the better modification in longer time.

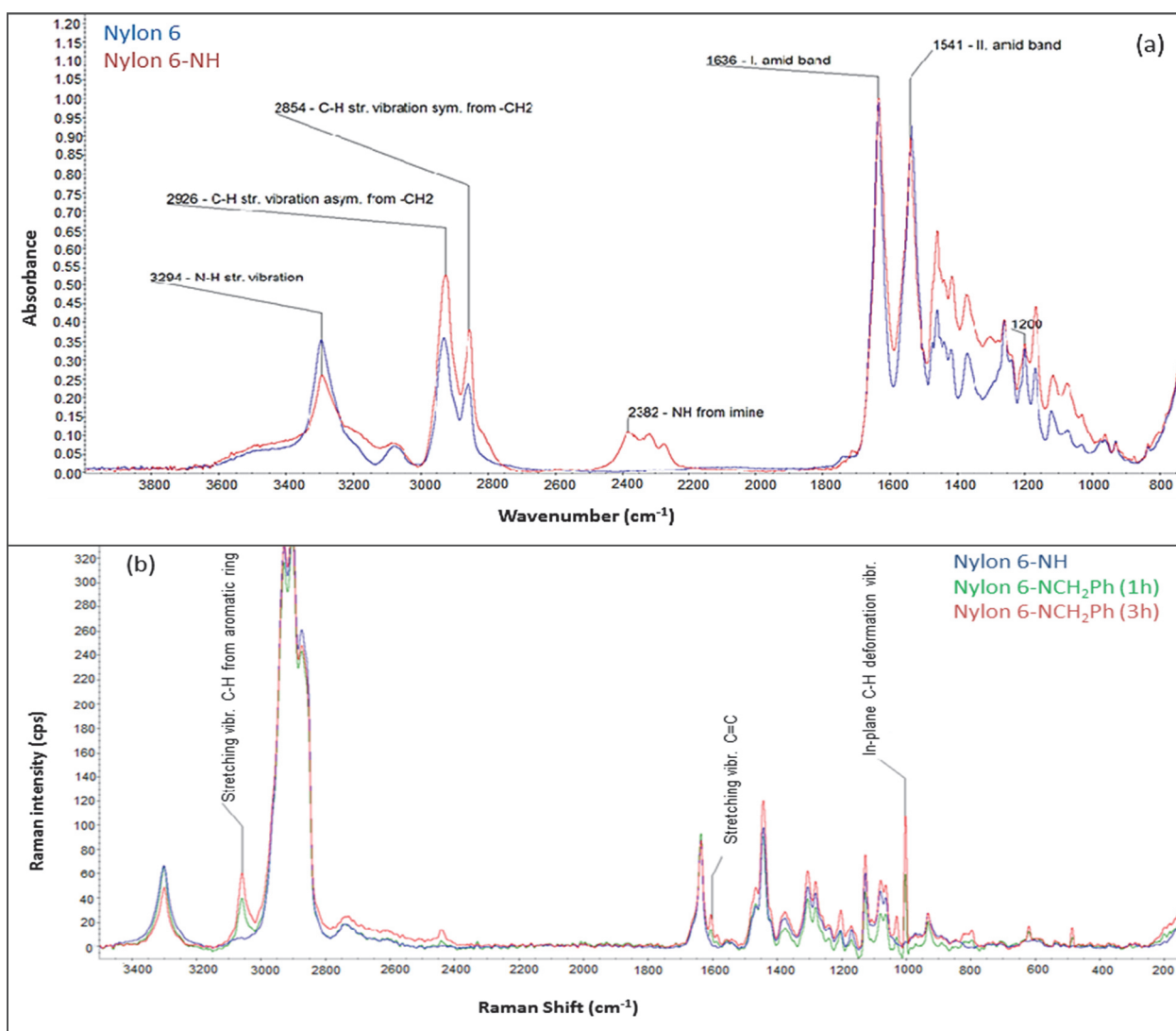


Figure 3 FT-IR spectra of unmodified nylon 6 and modified nylon 6-NH (a); Raman spectra of further modification from nylon 6-NH to nylon 6-NCH₂Ph (b)

3.5. AFM analysis

The AFM values of surface roughness (R_a) obtained in two different areas (10 x 10 μm and 1 x 1 μm) for unmodified nylon 6 and modified nylon 6-NH, nylon 6-NCH₂Ph indicated significant change in the roughness

after chemical reaction of nylon 6; thus confirmed the surface modification. Obtained Ra values are presented in the **table 1**.

Table 1 The changes in Ra values before and after surface modification of nylon 6

Samples Surface area	Nylon 6	Nylon 6-NH	Nylon 6-NCH ₂ Ph (1 h)	Nylon 6-NCH ₂ Ph (3 h)
(10 x 10) μm ²	34.8 nm	25.9 nm	138.3 nm	187.6 nm
(1 x 1) μm ²	5.1 nm	17.1 nm	22.3 nm	21.0 nm

4. CONCLUSION

The both non-spectral and spectroscopic methods as well as microscopic analyses confirmed that the naturally abundant surface amide groups of nylon 6 were successfully and efficiently reduced to amine groups which have been further modified by N-alkylation reaction of amines after reduction. The model reaction of N-alkylation of nylon 6-NH to nylon 6-NCH₂Ph confirmed the future scope of tuning the polymer surface to graft other functional groups using various compatible reagents for broader spectrum of applications including biomedical field. The modified surfaces are expected to be biocompatible due to the presence of amine groups. The FSEs of modified surfaces were in the range between 33 mJ/m² and 26 mJ/m². Mentioned values are expected to be an ideal for lowest bacterial adhesion and biofilm formation. This approach opens up new possibilities for surface modification of polyamides, particularly nylon 6.

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