Surface Modification and Thermal Bonding in COC Polymeric Microfluidic Chip

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Abstract

The field of polymer microfluidics, more broadly termed as 'Lab on a Chip' (LOC), is an interdisciplinary effort that combines aspects of physics, chemistry, nanotechnology and biotechnology. Cyclic olefin copolymers (COC) are the most widely used polymers for the fabrication of microfluidic devices due to its excellent transparency, low dielectric loss, low moisture absorption, good chemical resistance and the availability of a variety of grades with different glass transition temperature. Bioadhesion on polymer microchannel surfaces can happen during the separation process due to hydrophobic character of the COC surface. Accumulation of the adhered biomolecules can lead to coagulation, resulting in obstruction in the flow of the liquids through the micro channels thus causing system failure due to channel blockage. Moreover, thermal bonding and surface modification are two major issues in research to enhance the efficiency and performance of bioMEMS. In this study we explore the surface modification process and its influence on the interface bond strength in COC microfluidic chips. Surface modification of COC microchannels was carried out by UV-photografting of hydrophilic monomer and the results were characterized using contact angle and FTIR. The tensile bond strength test results showed significantly increased bond strength values in the modified chips. Moreover, the UV-photografted samples showed excellent hemocompatibility as it inhibits the blood cell adhesion and aggregation.

Keywords*: polymer, glass transition temperature, bioadhesion, UV-grafting, copolymer, cell adhesion.*

1 Introduction

Polymer based microfluidic devices have been widely used in lab-on-chip application due to their low cost, disposability, device efficiency and high throughput [1, 2]. A wide variety of polymeric materials such as poly (methyl methacrylate) (PMMA) [3], polycarbonate (PC) [4], polydimethylsiloxane (PDMS) [5], cyclic olefin polymers (COP) [6], and cyclic olefin copolymers (COCs) [7, 8] have been investigated for microfluidic device, but in recent days COC polymer have gained much popularity due its excellent transparency, low dielectric loss, low moisture absorption, good chemical resistance and the availability of a variety of grades with Tg. Despite the many advantages of COC, it has some limitations. Microfluidic devices constructed with COC polymers are not optimal for studies involving clinical diagnostics because of its intrinsic hydrophobic surface, which makes it susceptible to spontaneous nonspecific protein adsorption and cell adhesion when exposed to biological tissues or fluids. This can be detrimental to the device performance because uncontrolled cell adhesion and protein adsorption may cause blockage of the microchannel and eventually disrupt the flow of the fluids. Hence, to minimize these problems, it is necessary to chemically modify the COC surfaces.

Several methodologies including plasma treatment [9], ultraviolet (UV)/ozone oxidation [10], dynamic coating with hydrophilic polymers [11], and UV-photografting of hydrophilic polymers [12] have been employed for the surface modification of polymer microchannles. Among the strategies above, surface modification by UV-photografting is of great importance because it allows stable hydrophilic surface with controllable binding of graft chains with a high density, fast reaction rate, low processing cost,

easy process implementation, and modification of a shallow region near the solid surface without substantially changing the bulk properties.

In this paper we have demonstrated a simple novel surface modification technique for the fabrication of COC capillary electrophoresis chips with excellent biocompatible channel surfaces by UV-photografting of Acrylic acid (AAc) monomers. The effect of surface grafting on the bond strength and optical transparency are also outlined.

2 Experimental

2.1 *Materials and chemicals*

In this study, cyclic olefin copolymer (COC) resin, comprising Topas 5013 (Ticona, Florence, KY, U.S), with Tg of 130°C, was selected as the substrate material. Polymer sheets of dimensions 75 mm × 25 mm × 1 mm were injection molded at 270°C from the pellets using a Battenfeld injection moulding HM 25/60. Prior to injection molding, the resins were dried for 8 hours under vacuum at 20°C below their Tg to remove any moisture. The sheets were then cut into the desired sizes for further use as polymer substrates for UV-grafting. The homopolymer Acrylic acid of 99% purity and benzophenone (98% purity) photo-initiator were all purchased from Sigma Aldrich, Singapore.

2.2 *Preparation of COC microfluidic chips*

Capillary electrophoresis microchip containing microchannels that were 50 µm wide and 50 µm high (aspect ratio around 1) were embossed in the injection molded COC substrate using a silicon die. The silicon die was prepared using the DRIE technique. Hot embossing was carried out at 140°C and 2.94 kPa with a holding time of 4 min using a Specac hydraulic press. The patterned COC substrates were peeled off from the silicon die upon cooling of the set-up to room temperature, after which holes that acted as reservoirs were punched in the substrate. Finally, chips were made by thermal bonding another flat Topas 5013 substrate onto the base substrate containing the microchannels. An LOC which had sealed channels was thus obtained.

2.3 *UV-grafting on the COC substrate*

The ultra-violet (UV) grafting process was performed using a UV flood curing system (Techno Digm, Singapore). The UV (λ = 365 nm) intensity was adjusted by changing the distance from the UV lamp to the substrate. This distance was kept constant at 70 mm in the experiments. Initially, AAc solutions with 5, 15, and 25 wt% monomer concentration in water were prepared. Next, a solution containing 10 wt% of benzophenone (BP) photo-initiator in acetone was added to the above AAc solutions and stirred to ensure good mixing. The substrates were then exposed to UV light from the top to perform the polymerization reaction. The modified substrates were thoroughly cleaned by methanol and water solutions to remove the ungrafted monomers, homopolymers and loose polymers.

2.4 *Surface characterizations and Burst Pressure Test*

Static water contact angle measurements were made using a video-based FTA 200 video Series contact angle apparatus. For each sample, at least four different spots were measured and the data were averaged.

The chemical compositions of the untreated and treated surfaces were determined using a Perkin-Elmer GX Fourier transform infrared spectroscope (FTIR) equipped with an attenuated total reflection (ATR) unit.

The integrity of the thermal seal and the performance of the thermally sealed microdevice were assessed using a burst pressure test. During testing, the chip was connected to a syringe pump (ISCO Teledyne Technologies Company, Model 100DM), which was fitted with a pressure transducer with an accuracy of 0.5% in the range of 0.069–68.9 MPa. We followed the same procedure as described in our earlier article [13].

Thermal bonding and bond strength was carried out using a Carver laboratory hot press. The bonding pressure and bonding time were kept constant at 2.2 MPa and 6 min respectively. The bond strength of the modified and pure COC substrates was determined using lap shear specimens in an Instron 1130 tensile testing machine at a crosshead speed of 0.5 mm/min. The thickness of each substrate was 1 mm and the specimens had an overlap area of 15 × 10 mm^2. Four samples were tested for each specimen condition.

2.5 *Platelet adhesion*

The interactions between blood and the COC samples were studied using the platelet adhesion experiment.

The experiments were conducted using fresh platelet-enriched plasma (PRP) that was isolated from human blood and the detail of the process can be found in our earlier literature [13].

3 Results and discussion

The effect of UV irradiation time and monomer concentrations on the surface wettability of COC is shown in figure 1. It can be seen from figure 1a that contact angle decreased with increasing irradiation time. The contact angle of pure COC was 87° which was significantly decreased to 11-13° after grafting with AAc. The decreasing contact angle value indicates that UV-photografting of AAc monomer makes the COC surface more hydrophilic and it (hydrophilicity) increases with irradiation time due to more extensive polymerization of the AAc. It is also apparent from figure 1b that the contact angle of COC surfaces decreases with increasing the monomer concentrations. This can be attributed to the covalent attachment of a larger number of hydrophilic poly(acrylic acid) chains to the COC backbone.

In order to confirm the attachment of the functional groups on the COC surface, ATR-FTIR was performed. figure 2 shows the FTIR spectra of a typical AAc grafted COC substrate for varying irradiation times compared to the unmodified COC. For the pure COC, the peaks in the range 2937–2864 cm^{-1} and at 1454 cm^{-1} indicates the C-H stretching and bending which are in good agreement with the earlier reports [13].The peak at 1633 cm^{-1} in the monomer corresponds to the unsaturated C–C double bond. However, this peak disappeared after UV grafting which indicated that the C–C double bond was converted to C-C single due to the polymerization reaction. For the AAc grafted COC, the absorption bands at 3424, 1705, and 1000–1200 cm^{-1} correspond to the OH, C=O, and C-O stretching bands, respectively. Moreover, the more intense peak at 1727 cm^{-1} for the longer irradiated modified samples is indicative of the higher degree of AAc grafting on the COC substrate. These results confirmed that AAc has been successfully grafted onto the surface of the COC film.

Thermal bonding was studied next because it is an essential step for obtaining closed microchannels in a lab-on-a-chip system. It is apparent from figure 3 that all the UV photografted samples could be thermally bonded at temperatures significantly below the Tg (130°C) of the Topas substrate. It can be seen from figure 3 that photografting of AAc led to significant improvement in the bond strength and the bonding strength at 100°C for the grafted samples was much higher than that of the untreated COC substrates that could only be bonded at 120°C and higher.

The bond strengths for the other grafted samples with variation of monomer concentrations are represented in Table 1. The bond strength for the 5%, 15% and 25% monomer concentrated grafted samples were ~ 41%, 125% and 146% higher than that of the unmodified sample. These results indicate the formation of higher number of poly (acrylic acid) chains with increasing the monomer concentrations, leading to increase the bond strength by chain entanglement.

The typical burst pressure test data for COC chips prepared from the different grafted samples are listed in Table 2. It is apparent from Table 2 that the burst pressure increased significantly with increasing monomer concentration and bonding temperature. The chip that was photografted with 25% monomer solution and then bonded at 120°C exhibited a very high burst pressure of 3.5 MPa. These results suggest that UV grafting with AAc is a very effective process of producing strong and robust COC microfluidic devices.

The integrity of the device after thermal bonding was ascertained from the assessment of the cross-sectional profile of a section and polished LOC using the scanning electron microscope (SEM). It can be seen from figure 4 that the two polymer plates were bonded very well without affecting the shape and size of the sealed microchannels. Moreover, the straight microchannel walls indicated successful bonding and that high quality COC chips with good dimensional integrity were obtained.

The hemocompatibility/blood compatibility of the COC films after photografting was investigated next. figure 5 shows the SEM micrographs of the *in vitro* platelet adhesion for the pure COC and AAc grafted COCs. It can be seen that there were more adhered platelets on the untreated COC substrates and some of the platelets were aggregated to form thrombi. In contrast, a lower number of adhered platelets was noticed on the AAc grafted COC films. Compared to the untreated COC (Figure 5a) surface, the 15% (Figure 5b) and 25% AAc grafted COCs (Figure 5c) showed about 47% and 61% reduction in platelet adhesion. This indicates that the grafting of acrylic acid chains onto the COC surface can effectively reduce the number of adherent platelets. These

results might be ascribed to the -COOH group from the acrylic acid homopolymer which reduced the degree of platelet adhesion on the treated COC surface. These results are in good agreement with Lee et al [3] and Fougnot et al. who reported that the incorporation of carboxylic acid and carboxylate groups into polymers can significantly improve their blood-compatibility.

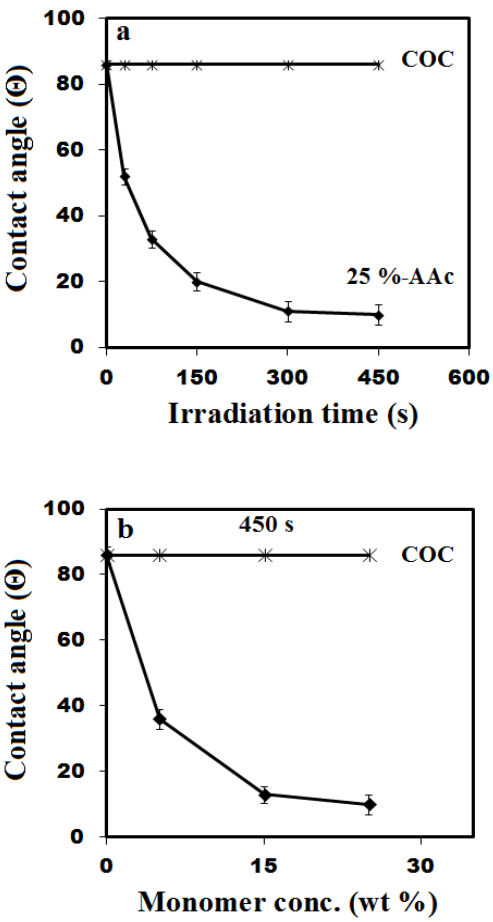


Figure 1: Variation of contact angle with (a) exposure time for 25 wt% (b) monomer concentrations at an irradiation time of 450s.

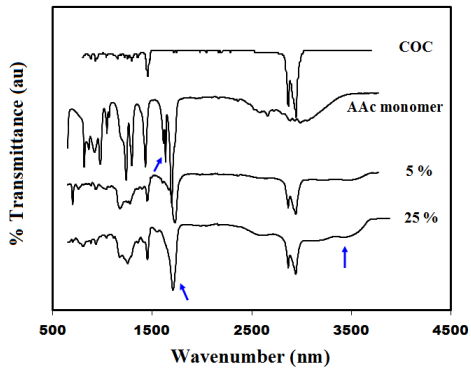


Figure 2: Typical FTIR spectra of COC, pure monomer, and 5% and 25% monomer grafted COC substrates.

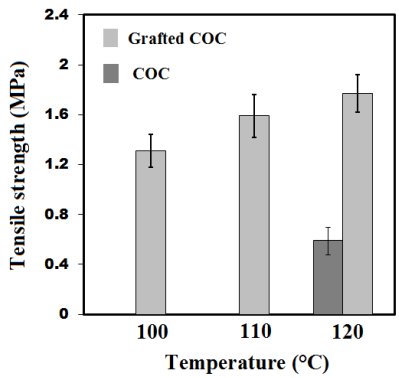


Figure 3: Effect of bonding temperature on the lap shear strength of the untreated COC and AAc photografted (25%) COC.

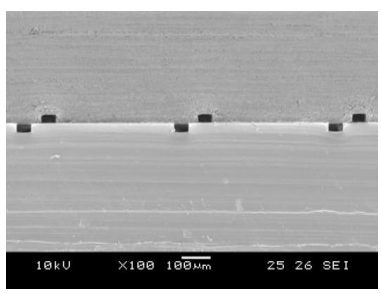
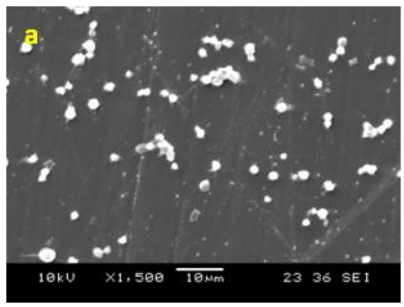
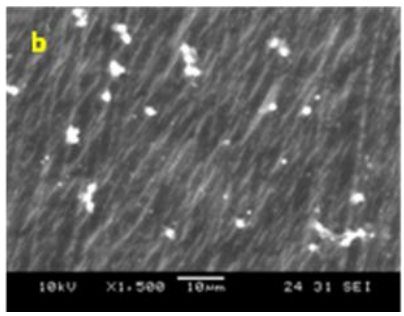


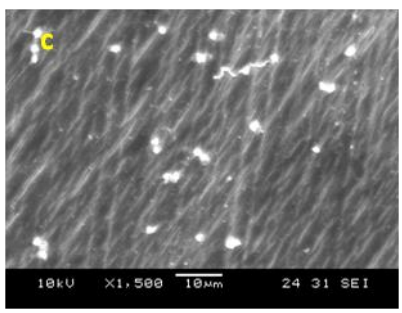
Figure 4: SEM micrograph of polished cross-section of COC microchannels in thermally bonded chip (channel depth and width: 50µm× 50µm).



(a)



(b)



(c)

Figure 5: SEM micrographs of the adhered platelets on (a) untreated COC (b) 15% and (c) 25% monomer grafted COC.

Table 1: Effect of monomer concentrations on lap shear strength. [Bonding conditions: T = 110°C, P = 2 MPa and t = 6]

Sample	Tensile strength (MPa)	Increment (%)
Pure COC	0.59 (± 0.11)	-
5 % AAc-g- COC	0.83 (± 0.15)	41
15 % AAc-g- COC	1.33 (± 0.20)	125
25 % AAc-g- COC	1.45 (± 0.23)	146

Table 2: Effect of monomer concentrations on burst pressure for the UV-grafted COC chips.

Sample	Burst Pressure strength (MPa) [± 0.30 MPa]
Pure COC	1.68
5% AAc-g- COC	2.16
15% AAc-g- COC	3.18
25% AAc-g- COC	3.50

4 Conclusions

The UV-photografting of AAc is useful for modifying COC substrates for applications in microfluidic devices. The AAc modified surfaces are more hemocompatible and can be thermally bonded at 30°C below the Tg of COC which enables the channel dimensional integrity to be preserved. Significantly higher burst pressures were obtained with the AAc UV-photografted samples which permits robust COC chips to be made.

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