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Finite Element Stress Analysis of Optical Fiber due to Mechanical Expansion of Hydrogel Coating

Ian Yulianti[1,2, a], Abu Sahmah M. Supa'at[1,b], Sevia M. Idrus[1,c]
Ojo Kurdi[3,d] , and M. Ridwanto S. Anwar[1,e]

[1]Universiti Teknologi Malaysia, Malaysia

[2]Universitas Negeri Semarang, Indonesia

[3]University Selangor, Malaysia

[a]ianyulianti@fkegraduate.utm.my, [b]abus@fke.utm.my, [c]sevia@fke.utm.my, [d]ojokurdi@unisel.edu.my, [e]shabab_82@yahoo.com

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Abstract. This paper presents the stress analysis in optical fiber due to swelling of hydrogel material coated on it. The silica optical fiber was assumed to be coated by hydrogel that consists of hydroxyethyl methacrylate, acrylic acid and ethylene glycol dimethacrylate as crosslinker. The hydrogel swelling was modeled using free energy function. The conditional equilibrium of hydrogel was solved using finite element method and the stress induced in optical fiber was simulated simultaneously. The simulations were done for two hydrogel coating thickness values, 30 μm and 40 μm. Etched optical fiber coated by 40 μm hydrogel was also simulated. The results show that maximum stress in optical fiber is higher for thicker hydrogel thickness and is higher for etched optical fiber. Maximum stress magnitudes at all pH values are below tensile strength of optical fiber.

Introduction

Optical fiber (OF) has been widely employed for sensor application to measure various measurands such as strain, temperature, humidity, chemicals, pressure, electric field and several other environmental factors. Swelling sensing material is frequently used to induce a mechanical effect on OF for certain sensor applications, mostly in optical chemical sensor based on fiber Bragg grating (FBG) technique. Lu *et al*. [1] have used acrylate and polyimide polymers to coat FBG to measure sugar and potassium chloride. Polyimide and thermoplastic polyimide have been sequentially used to coat FBG for measuring humidity [2-3]. Hydrogel has been used as coating material to realize salinity sensor [4] and pH sensor [5] by adopting FBG technique and long period grating (LPG) technique, respectively.

The sensing principle of swelling material based OF sensors relies on the mechanical effect induced on the OF by volume expansion of the swelling material coated on it. Using intensity modulated technique, the volume expansion of swelling material induce microbends in an OF which further induce losses of light such as demonstrated by Michie *et al*. [6]. Whereas, in FBG based sensor, the strain in OF induced by the swelling action of coated material results in shift of Bragg wavelength [1, 4, 7-8]. Increasing the mechanical response induced by the swelling of coated material will increases the sensor sensitivity. The mechanical response could be increased by increasing the coated material thickness or by reducing fiber diameter. However, the increase of mechanical response means the increase of stresses. Therefore, optimization should be made by considering trade-off between sensitivity and physical reliability. This paper investigates the stress in OF induced by pH sensitive hydrogel coating. The pH sensitive hydrogel coated OF can be used as optical pH sensor [9]. The inhomogenous swelling of hydrogel due to OF as mechanical constraint was modeled using free energy function as proposed by Marcombe *et al*. [10]. The free energy function was solved using finite element method by adopting ABAQUS software so that the stress and strain induced on the OF could be solved simultaneously.

Methods and Finite Element Modeling

pH Sensitive Hydrogel Swelling Model. pH sensitive hydrogels are considered as polymers chain with a three-dimensional network contain acidic or basic groups bound to the chains. The acidic groups on the chains deprotonate at high pH, whereas the basic groups protonate at low pH. A change in the pH of the solution surrounding the gel will initiate a physical process of either gel swelling or deswelling [11].

The swelling of hydrogel coated on OF is inhomogenous due to mechanical constraint of OF. To model the inhomogenous swelling of the pH sensitive hydrogel, a model developed by Marcombe *et al.* [10] was implemented. The model was developed by represents the free-energy function as a functional of the field of deformation by using a Legendre transformation. The free-energy density of the gel is a sum of free-energy density due to stretching networks (W_{net}), due to mixing the solvent with the network (W_{sol}), due to mixing ions with the solvent (W_{ion}), and due to dissociating the acidic groups (W_{dis}) as defined by

$$W=Wnet+Wsol+Wion+Wdis. \tag{1}$$

where

$$W_{net} = \frac{1}{2} NkT\left[F_{ik}F_{ik} - 3 - 2\log(\det\mathbf{F})\right]. \tag{2}$$

$$W_{sol} = \frac{kT}{\upsilon s}\left[(\det\mathbf{F}-1)\log(1-1/\det F) - \frac{\chi}{\det\mathbf{F}}\right]. \tag{3}$$

$$W_{ion} = kT\left[C_{H^+}\left(\log\frac{C_{H^+}}{c_{H^+}^{ref}\det\mathbf{F}} - 1\right) + C_+\left(\log\frac{C_+}{c_+^{ref}\det\mathbf{F}} - 1\right) + C_-\left(\log\frac{C_-}{c_-^{ref}\det\mathbf{F}} - 1\right)\right]. \tag{4}$$

$$W_{dis} = kT\left[C_{A^-}\left(C_{A^-} - \log\frac{C_{A^-}}{C_{A^-}+C_{AH}}\right) + C_{AH}\left(\log\frac{C_{AH}}{C_{A^-}+C_{AH}}\right)\right] + \gamma C_{A^-}. \tag{5}$$

kT is the temperature in the unit of energy, N is the number of polymer chains divided by the volume of the dry network, F_{ik} is the deformation gradient of the network, ν is the volume per solvent molecule, χ is dimensionless parameter, C_{H+}, C_{A-}, C_{AH}, C_+ are the nominal concentration of proton, fixed charges, acidic group, and co-ion and $c^{ref}{}_{H+}$ and $c^{ref}{}_{+}$ are the reference concentration of proton and co-ion. To be implemented in finite element software, the free-energy function was represents using Legendre transformations. After transformations, the condition of equilibrium of the gel has the same form as that of hyperelastic material.

Hydrogel Coated OF Specification and Modeling. The structure of the OF coated by pH sensitive hydrogel under study is depicted in Fig.1. The OF was assumed to be a standard single mode fiber (SMF) for optical communication application with fused silica as the material. Core, cladding and acrylic buffer diameter are 9 μm, 125 μm and 250 μm, respectively. At the region where hydrogel is coated, acrylic buffer is removed. Aluminum disks are located at the end of the unbuffered region to prevent hydrogel from expanding in longitudinal direction. The pH sensitive hydrogel was assumed to be hydroxyethyl methacrylate (HEMA), acrylic acid and ethylene glycol dimethacrylate as crosslinker [11-12]. The Young modulus of hydrogel in the dry network (unswollen), NkT, is 0.29 MPa [12]. At room temperature, kT= 4×10^{-21} J and $\nu=10^{-28}$ m^3 [10]. χ was obtained by fitting the experimental result provided by De *et al*. [12]. The mechanical properties of OF and acrylic buffer are tabulated in table 1.

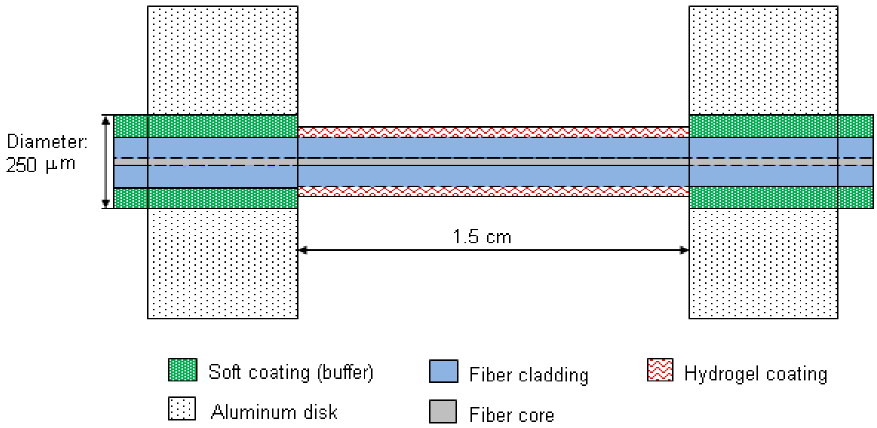


Figure.1 Schematic 2D layout of optical fiber coated by pH sensitive hydrogel.

The simulations were done for two hydrogel coating thickness values, which are 30 µm and 40 µm. In order to investigate the mechanical response in etched fiber, simulation was also done for fiber cladding diameter of 40 µm with hydrogel coating thickness of 40 µm. The equilibrium condition of gel was implemented in ABAQUS by using hyperelastic material user-defined subroutine code [10]. The hydrogel coating was assumed to be compressible and was meshed using 8-node linear brick, hybrid element with enhanced hourglass control (C3D8RH) whereas the OF was meshed using 8-node linear brick (C3D8R). Due to symmetry, the simulations were done for half of model and *z* symmetry boundary condition was implemented.

Table 1. Mechanical properties of OF and buffer material.

Properties	Silica Optical Fiber	Acrylic (Buffer)
Young's modulus [MPa]	73×10^3	2.8
Poisson's ratio	0.165	0.37
Tensile strength [MPa]	110	69

Results and Analysis

Finite element simulations show that uniform Von Misses stress field occurred in the hydrogel coated OF region (unbuffered region). However, in the area near buffered OF, significant non uniform stress distribution exists and maximum stress occurred as shown in Fig.2 (a). This condition occurred for all pH values for both hydrogel coating thicknesses and also for etched OF. In hydrogel coated region, the stress values are in the order of hundreds of kPa in acidic solution (pH < 4) and in the order of MPa in pH range of above 4. The plot of stress values along *z* direction on OF core is depicted in inset in Fig. 2(a). The stress begins to increase at distance of 0.01 cm from the buffered region. The maximum stress values at pH range of 2 to 9 are depicted in Fig. 2(c). It is shown that higher coating thickness induced higher stress on OF. It is also shown that by reducing fiber diameter, the induced stress increased. Significant increase of stress occurred at pH range of 4 to 7. At pH of above 7, the stress is almost constant. All stress magnitudes are below tensile strength of OF, thus it is still inside reliability margin.

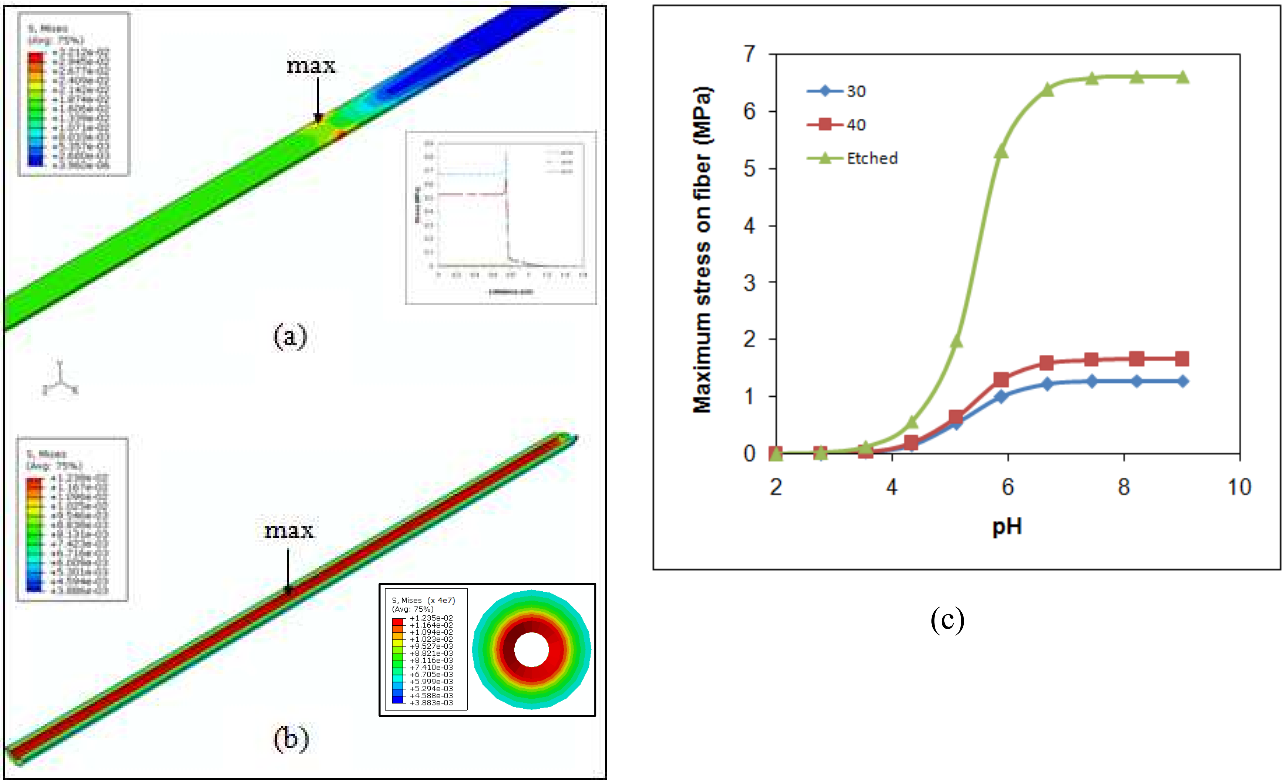
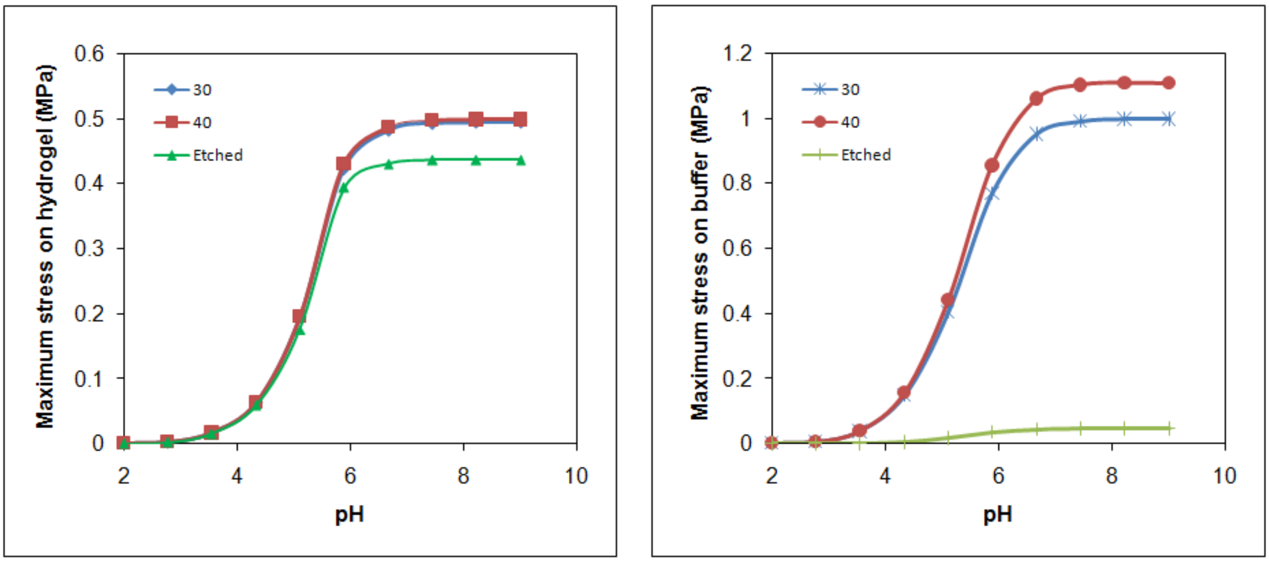


Figure 2. Stress distribution of 30 μm hydrogel coated OF at surrounding pH of 8 on OF (a), on hydrogel (b) and maximum induced stress on OF at various surrounding pH values for hydrogel thickness of 30 μm,40 μm and etched fiber with hydrogel coating thickness of 40 μm (c).

As expected, high stress magnitude occurred in hydrogel near the interface between hydrogel and OF due to the constraint of OF as shown in Fig. 2(b). Moving away from the interface, the stress decreases as the radial distance increases as shown in the inset in Fig 2(b). The maximum stress values in hydrogel are plotted as function of surrounding pH value as depicted in Fig. 3(a). It is shown that stresses in hydrogel that is coated on etched OF are lower than that in hydrogel coated on unetched OF, especially at pH of above 6. Stress value as high as 0.5 MPa occurred in hydrogel coated on unetched fiber when it is subjected to surrounding pH of above 7.



(a) (b)

Figure 3. Maximum induced stress on hydrogel (a) and on buffer (b) at various surrounding pH values for hydrogel thickness (30 μm and 40 μm) and for 40 μm hydrogel coated on etched OF.

At acrylic buffer, high stress distribution and maximum stress value occurred at the interface between buffered region and unbuffered region. The maximum stress values are plotted against pH values as depicted in Fig. 3(b). It is clearly shown that induced stress in acrylic of etched OF is much lower than that of unetched OF. As in OF, it is also shown that induced stresses in acrylic buffer are higher for higher hydrogel coating thickness. The maximum stress magnitude is below tensile strength of acrylic. The stress near interface is in the order of hundreds of kPa and decrease to around 2 kPa for pH value of above 7.

Concluding Remarks

Stress analysis of OF due to swelling action of pH sensitive hydrogel coating has been demonstrated using finite element method. The simulations were done for two hydrogel coating thickness values. The results show that the maximum stress induced in OF occurred at the interface between unbuffered region and buffered region. From the distance of 0.01 cm from buffered region, high stress distribution start to occur. At hydrogel, along axial direction, high stress distribution exists at the region near the interface between hydrogel and OF. Simulation was also done for hydrogel coated on etched fiber. It is shown that by etching the fiber, the stress magnitudes are increase in OF but decrease in hydrogel as well as in acrylic buffer. Maximum stress values at all pH of all models are below tensile strength of silica OF.

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References

[1] P. Lu, L. Men, and Q. Chen, Sensors Journal, IEEE, Vol. 9 (2009), p. 340-345
[2] X. F. Huang, D. R. Sheng, K. F. Cen, and H. Zhou, Sensors and Actuators B: Chemical, Vol. 127 (2007), p. 518-524
[3] T. L. Yeo, T. Sun, K. T. V. Grattan, D. Parry, R. Lade, and B. D. Powell, Sensors and Actuators B: Chemical, Vol. 110 (2005), p. 148-156
[4] X. Liu, X. Zhang, J. Cong, J. Xu, and K. Chen, Sensors and Actuators B: Chemical, Vol. 96 (2003), p. 468-472
[5] M. C. Jesus, R. M. Ignacio, V. Ignacio del, and J. A. Francisco, Sensors Journal, IEEE, Vol. 7 (2007), p. 455-463
[6] W. C. Michie, B. Culshaw, M. Konstantaki, I. McKenzie, S. Kelly, N. B. Graham, and C. Moran, Lightwave Technology, Journal of, Vol. 13 (1995), p. 1415-1420
[7] K. Schroeder, W. Ecke, and R. Willsch, Optics and Lasers in Engineering, Vol. 47 (2009), p. 1018-1022
[8] B. Sutapun, M. Tabib-Azar, and A. Kazemi, Sensors and Actuators B: Chemical, Vol. 60 (1999), p. 27-34
[9] I. Yulianti, A. S. M. Supa'at, S. M. Idrus, N. M. Kassim, and A. M. Al-Hetar, "Fiber Bragg grating based pH sensor," in *Enabling Science and Nanotechnology (ESciNano), 2010 International Conference on*, 2010, pp. 1-2.
[10] R. Marcombe, S. Cai, W. Hong, X. Zhao, Y. Lapusta, and Z. Suo, Soft Matter, Vol. 6 (2010), p. 784-793
[11] S. K. De and N. R. Aluru, Mechanics of Materials, Vol. 36 p. 395-410
[12] S. K. De, N. R. Aluru, B. Johnson, W. C. Crone, D. J. Beebe, and J. Moore, Microelectromechanical Systems, Journal of, Vol. 11 (2002), p. 544-555

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