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A Self-Repairing Natural Rubber as a Novel Material Pad to Develop an Electro-Surgical Training Prototype

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Abstract

This work aims to develop a self-repairing natural rubber sheet and use it in a new design electro-surgical training prototype. The self-repairing material is prepared via controlled crosslinking with varying curing time and temperature and applied as a material pad. The electrical circuit board in the prototype is created to measure the depth of the surgical blade through a material pad. The completely modified control crosslinking of the rubber sheet is confirmed by the changing chemical structure of rubber latex via FT-IR spectra resulting in the hardening of swelling affected by high crosslinking density. The self-repairing of natural rubber sheets occurred at the cut part and the tensile strength at break increases with the increase in self-repairing time. The prototype testing shows that when the scalpel blade is cut into the rubber sheet at the setting dept, the electrical circuit is activated, making it suitable for medical practice.

Keywords: self-repairing natural rubber, electro-surgical training, medical students, surgical practice, surgical material pad

1. Introduction

Surgical skills are an essential practice in medical study. They are critical processes in medical training for medical students. For surgical training and practice, students use scalpel blades and skin training pads for surgical training skills [1-19]. Generally, the surgical training classroom uses various components, such as chicken trunks, wings, or thighs, as used by Denadai et al. [1] to practice surgical skills. Okhovat et al. [2] studied surgical training with the head and neck of lamb, suckling pig, and rabbit. Azari et al. [3] compared hand motion training suturing on foam, porcine feet, and bowel. Evgeniou et al. [4] showed that intermediate and advanced surgical training skills have been using cadaveric animals, cadaveric humans, and live animals. Illston et al. [5] created the operating model using beef tongue, beef tripe, and chicken leg segments. However, these materials have disadvantages as animal components are easily perishable. Moreover, the synthesis material is developed for surgical training material. The surgical study [6-7] has been using 3D printing with silicone material. Additionally, polylactic acid plastic was prepared for a 3D-printed suture pad trainer [8].

Marcondes et al. [9] presented the learning suture techniques using ethylene-vinyl acetate and plastic models [10]. Bhatti et al. [11] used a flat elastic band simulation for laparoscopic suturing. The anatomical model for surgical training [12] and cadaveric animal models [13] were created by a plastic material. Byrne and Aly [14] studied the natural and synthetic polymer as a suture material. The limit of the synthesis (silicone, plastic, or polymer) material is expensive, cannot be repeatedly used, and is complex to prepare. Therefore, researchers are interested in using other materials to practice surgery.

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Watanabe et al. [15] prepared an equipment of surgical using a fleece fabric. D'Angelo et al. [16] operated with simulated tissue types such as foam (dense connective tissue), rubber balloons (artery), and tissue paper (friable tissue). Capperauld and Hargraves [17] performed surgery on a polyurethane sponge as a disposable practice block. The synthetic microfiber cloth was used to simulate suturing on the board [18]. Coughlin et al. [19] simulated the foam board in the form of a synthetic membrane for training surgical skills.

However, the foam and sponge material are easily ripped apart. From the limits and disadvantages of that material mentioned above, this work is interested in developing and preparing a novel surgical training material pad via a modified controlled crosslinking of natural rubber as a self-repairing natural rubber sheet. A self-repairing natural rubber is a material able to repair mechanical damage on itself, and natural rubber is an exciting material to be modified with a self-repairing function because the flexibility of rubber chains is an advantage to rebuilding the chain interactions to repair mechanical damage [20]. A difference between self-repairing natural rubber and other surgical simulation materials is that self-repairing natural rubber can be repeated and repaired completely by itself. Self-repairing natural rubber is low-cost and simple to prepare.

The program computer of surgical simulation with 3D devices is widely available. Nevertheless, it is only used in large hospitals, and expensive, and difficult to access for study in medical student's lab. Meanwhile, in the general surgical training lab, the electrical circuit was not used to help practice and apply for surgical training [1-19]. When using only a surgical pad, the students cannot know how deep the scalpel blade will cut through. To solve this problem and improve the new experience of surgical training, new equipment must be created, and developed to increase surgical learning, and easy to access. The experiment created an electro-surgical training prototype using basic electronics and saved costs. The electrical circuit was designed for an electro-surgical training prototype.

Thus, this work aims to modify the vulcanization system to prepare a self-repairing natural rubber sheet for a surgical training pad. The crosslink density, swelling, Fourier transform infrared spectroscopy (FT-IR) spectra, and self-repairing time on the mechanical properties of a self-repairing natural rubber sheet were studied. The development of an electro-surgical training prototype was designed and created. The work function on the electrical circuit board of the prototype was tested. This device must still be developed to make simulation equipment for medical students' labs of basic surgical training.

2. Materials and Methods

This experiment was divided into two parts. Firstly, prepare the self-repairing rubber sheet using natural rubber latex and vulcanizing reagent under a controlled crosslinking process and confirm the self-repairing properties. Secondly, a new electrical circuit was designed to generate an electro-surgical prototype using electrical hardware. The work function of the prototype was tested.

2.1. Materials

Hardware required for electro-surgical training prototype was used switch (electronics Narathiwat, Thailand), light-emitting diode (electronics Narathiwat, Thailand), 2.7 kΩ resistor (electronics Narathiwat, Thailand), 3-24 V buzzer (electronics Narathiwat, Thailand), 9V (DC) battery (electronics Narathiwat, Thailand), and Cable wire clip (electronics Narathiwat, Thailand).

Materials and chemicals used to prepare the self-repairing natural rubber consisting of 60% natural rubber latex (Yala Latex Industry Co., Ltd., Thailand), 50% zinc oxide (Polymer Innovation Co., Ltd., Thailand), 50% sulfur (Shanghai Bosman Industrial Co., Ltd., China), 50% ZMBT, zinc 2-mercaptobenzothiazole (Polymer Innovation Co., Ltd., Thailand), and 50% ZDEC, zinc diethyl dithiocarbamate (Polymer Innovation Co., Ltd., Thailand).

2.2. The modified vulcanization system of natural rubber latex prepared a self-repairing natural rubber sheet using the controlled crosslink method

The pre-vulcanized natural rubber latex was prepared using natural rubber latex mixed with chemicals at 25 ± 5 °C or room temperature. The rubber sheet mold is filled with pre-vulcanized natural rubber latex as a self-repairing natural rubber sheet. The dried and vulcanized method of rubber sheet for controlled crosslinking is divided into two methods; the first method is at 30 °C or room temperature under UV lighting [21] was used for vulcanizing the rubber sheet for 7 days (Fig. 1) and placed on a table for 28 days. The second method is drying and curing at 40 °C (7 days), 50 °C (7 days), and 60 °C (7 days) using a hot air oven. The self-repairing natural rubber sheets are prepared at 2 mm thickness and set on top at layer 1 of the aluminum foil (layer 2) as a surgical training pad for the electro-surgical training prototype.

Fig. 1 The dried and cured self-repairing natural rubber sheets at 30 °C or room temperature under UV lighting

2.3. To study the controlled crosslinking of a self-repairing natural rubber sheet, and crosslink density and swelling properties

The controlled crosslinking process was employed to prepare a self-repairing natural rubber sheet. The self-repairing property of different curing times and temperatures of the rubber sheet was studied by determining crosslinking density using the Flory-Rehner equation and assessing swelling through a method compliant with ASTM D3616 – 95.

2.3.1. Crosslink density determination of a self-repairing natural rubber

The crosslink density of the natural rubber film was determined using the Flory–Rehner equation [20, 22-23] as follows:

$$-In\left(1-V_r\right)-V_r-\chi V_r^2=2V_s\eta_{swell}\left(V_r^{1/3}-\frac{2V_r}{f}\right) \tag{1}$$

where V_r is the volume fraction of rubber in swollen gel, χ is rubber – toluene solvent interaction parameter (0.3795), V_s is molar volume of the toluene (106.2 cm^3 mol^{-1}), η_{swell} is the cross-link density of the rubber (mol cm^{-3}), and f is functionality of the crosslinks (being 4 for the sulfur curing system).

$$V_r=\frac{\left(W_d-W_f\right)/\rho_r}{\left(W_d-W_f\right)/\rho_r+\left(W_s-W_d\right)/\rho_s} \tag{2}$$

where W_d is the weight of the de-swollen sample, W_f is the weight of the filler in the compound, W_s is the weight of the swollen sample, and ρ_s is the density of the toluene solvent (0.87 g/cm^3), and ρ_r is the density of the rubber (0.91 g/cm^3).

2.3.2. Swelling measurement of a self-repairing natural rubber

The rubber sheet sample was cut, weighed 0.39 to 0.41 g, and immersed in the toluene solvent into a bottle of 25 cm^3 or 25 mL. Cover the bottle and allow it to stand in the dark for 16 to 20 h or 48 h at 25 ± 2 °C. The weight of samples was measured before immersed in toluene solvent (dry samples) and after immersed in toluene (swollen samples). The swollen samples were taken out, and excess solvent on the surface was removed with tissue paper and weighed. The swelling percent at a time (Qt) [22] was calculated from the formula below and corresponding to ASTM D3616 – 95.

$$Q_t=\frac{\left(W_t-W_o\right)/W_o}{M_W}\times 100 \tag{3}$$

where W_o is the weight of the dry sample, W_t is the weight of the swollen sample, and M_W is the molar mass of toluene (92.14 g mol^{-1}).

2.4. Fourier transform infrared spectroscopy (FT-IR) analyzed the crosslinking reaction on the C=C bond of a self-repairing natural rubber sheet

The self-repairing natural rubber sheets were prepared using a controlled crosslink method and cured with the sulfur vulcanization system. The crosslinking reaction by sulfur mainly occurred on the C=C bond of natural rubber. FT-IR spectroscopy was used to study and detect the intensity signal of the C=C bond. The rubber sheet samples were cut to 1 cm × 1 cm. The attenuated total reflection (ATR) mode on a Bruker Tensor spectrometer was used in the wavenumber range of 3600-500 cm^{-1} with a resolution of 2 cm^{-1}, and FT-IR spectra were analyzed with OPUS software and recorded in terms of intensity (absorbance units, a.u.) and wavenumber (cm^{-1}).

2.5. Surface morphology of a self-repairing natural rubber sheet

ImageJ software was used to observe and analyze the surface of a self-repairing natural rubber sheet. Photographs (10× lens optical dimensions) were used to analyze using a surface plotter mode of ImageJ software. The separate parts and self-repairing phenomena on the rubber sheet surface were presented in 3D.

2.6. Mechanical properties of self-repairing inside separated parts on the surface of natural rubber sheet using tensile test

The tensile test was studied corresponding to ASTM D412. Three samples were cut from 1 mm thickness rubber sheets and were cured at 30 °C (7 days), 40 °C (7 days), 50 °C (7 days), and 60 °C (7 days). It was cut into two parts and reconnected via a self-crosslinking at 25-30 °C for 5 to 20 minutes. The sample was stretched by the load in a uniaxial direction until breaking and the tensile strength at the break was as follows:

$$TS = \sigma = \frac{F}{A} \tag{4}$$

where TS is tensile strength at break, σ is Uniaxial stress (N/m^2 or Pa), F is the applied load (N), and A is the original cross-sectional area (m^2).

2.7. *The electrical circuit development of the electro-surgical training prototype*

Basic electronics and electrical circuits are used to develop an electro-surgical training prototype. The circuit wizard program is used to create, design, and test the circuit board of the electro-surgical training circuit, as shown in Figs. 2-3. Fig. 2 shows that the switch is open; it breaks the circuit to stop the flow of electric current in the circuit, and positions 1 and 2 are disconnected. As a result, the light-emitting diode (LED) and buzzer do not work. When a switch is closed (Fig. 3(a)), it completes the circuit and allows electric current to flow, but positions 1 and 2 are still disconnected. The LED and buzzer do not work.

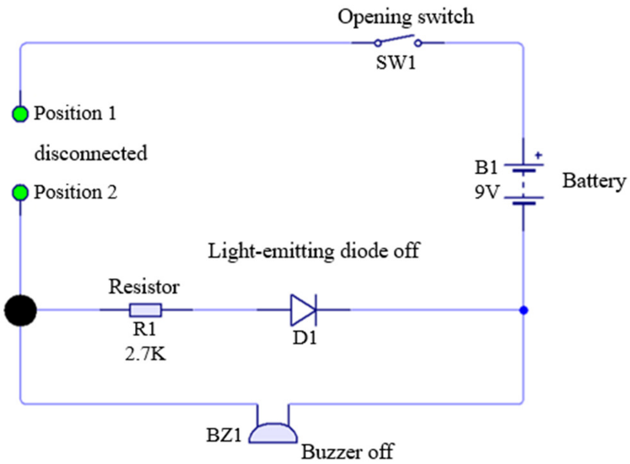
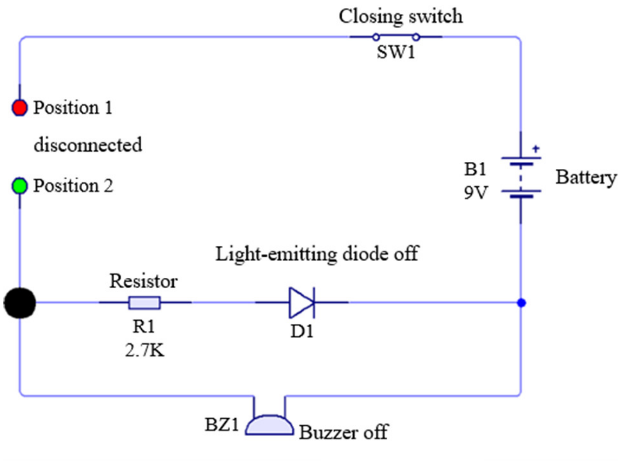
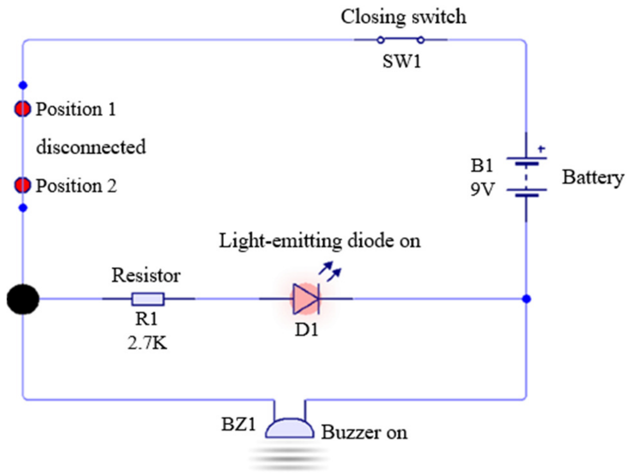


Fig. 2 Opening the switch of the electro-surgical training circuit diagram



(a) Position 1 and position 2 disconnected



(b) Position 1 and position 2 connected

Fig. 3 Closing the switch of the electro-surgical training circuit diagram

Meanwhile, positions 1 and 2 are connected, and the circuit is complete to activate the electric current, which will flow in the circuit and work by moving electrical energy as the electric current, driven by the voltage from a 9V battery on the circuit board. Direct current (DC) is one-directional. The cathode (positive) charge flows away from the positive part of the 9

V battery towards the anode (negative) part, moving through the circuit. The flow of electrons on a circuit is made by linking electrical components with conduct electricity. The resistor of 2.7 kΩ limits the current flow in the circuit. The middle of the circuit can attach any load, such as LED and buzzer when the electrons move from the source through the load and generate light and sound (Fig. 3 (b)) as followed by a flowchart (Fig. 4).

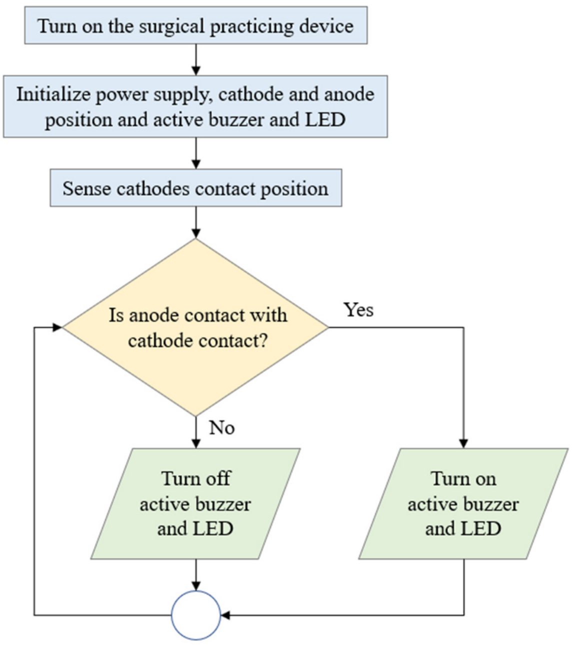
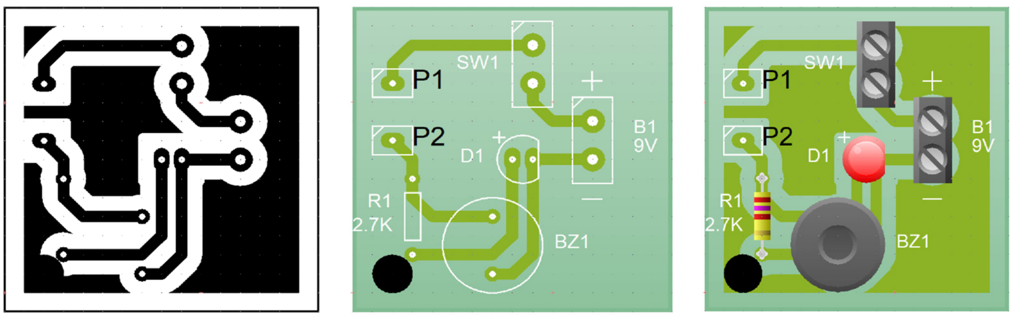


Fig. 4 Flowchart of basic electronics work for electro-surgical training prototype

The electrical circuits were tested and converted from a circuit diagram (Figs. 2-3) into the printed circuit board (PCB) layout (Fig. 5) and set up electrical components such as LED, buzzer, resistor, power source, and switch (Fig. 5 (c)) using the circuit wizard program as an electro-surgical training circuit.



(a) Artwork (b) Logic levels (c) Real printed

Fig. 5 Artwork, logic levels, and the actual printed circuit board (PCB) for the electro-surgical training prototype

2.7. The design model and work function of the electro-surgical training prototype

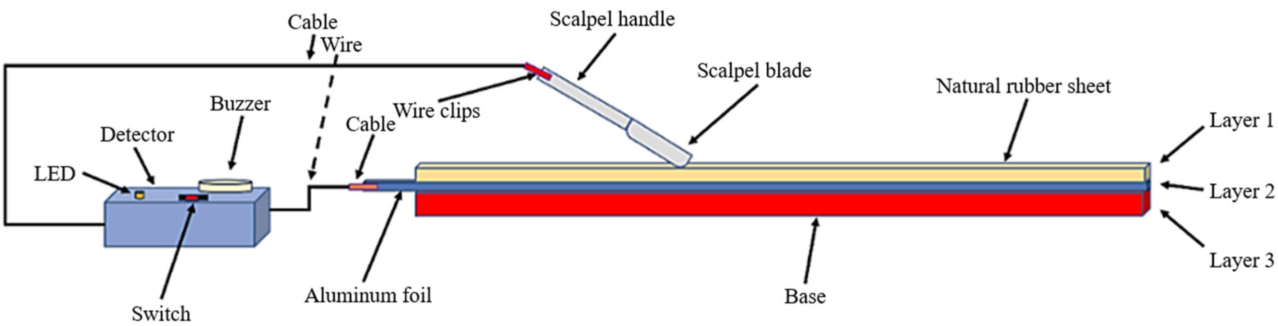


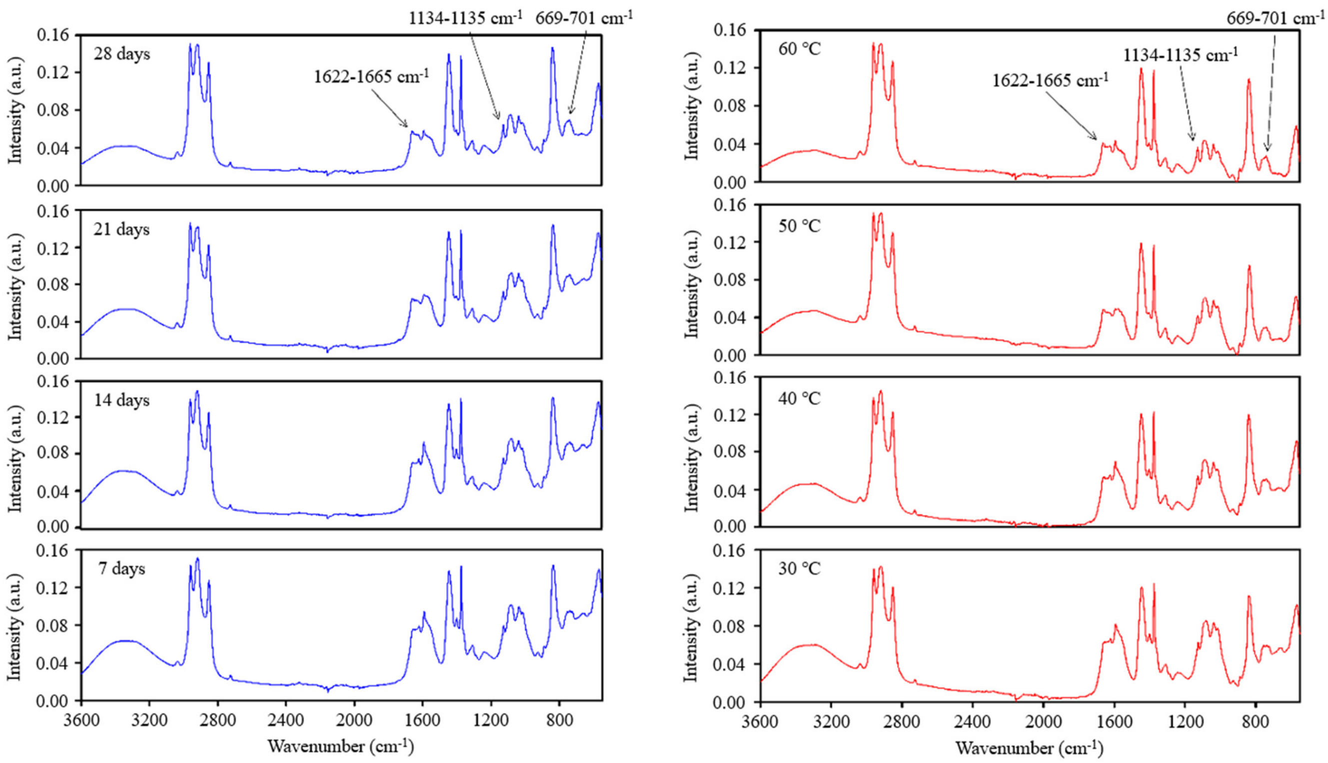
Fig. 6 The electro-surgical training prototype's design model and work function

This section will explore the electro-surgical training prototype's design model and work function. In constructing an electro-surgical training prototype, it is good to place the buzzer, LED, and switch on the top plastic case and set up the circuit board and battery inside the case. The wire is then placed at the side of the case by drilling smaller holes at both ends to keep the wire with cable wire clips (crocodile) to connect a scalpel handle and aluminum foil. The component surgical surface pad consists of 3 layers: a self-repairing natural rubber sheet in layer 1 that can be changed to set the thickness of the rubber sheet, and layer 2, an aluminum foil with foam base in layer 3, as follows the model in Fig. 6.

For working explanation, the switch is on, and one end of a battery is attached to the scalpel handle at position 1 on the PCB circuit board. The other end is attached to the aluminum foil at position 2 on the PCB circuit board. Suppose the user manages to move the scalpel blade along the natural rubber sheet surface (layer 1) and the depth of the scalpel blade without touching the aluminum foil (layer 2), the buzzer and LED do not work. If the depth of the scalpel blade touches the aluminum foil, it makes a fully connecting circuit of the components on the PCB board, and electric current flows from the battery to the buzzer and LED, which generates light and sound.

3. Results and Discussion

The surgical training pad preparation and the controlled crosslinking of the natural rubber sheet were prepared and vulcanized using methods 1 and 2. The general crosslink reaction between the sulfur vulcanized system and the natural rubber chain mainly occurs on the C=C (double bonds) [24-25]. For this reason, the controlled crosslinking of a self-repairing rubber sheet will focus on carbon double-bond changes. FT-IR spectra (Figs. 7(a) and 7(b) and Table 1) show that the signal peak indicates the C=C (Str.) bond [26-28] at 1662-1665 cm^{-1} decreased due to the unsaturated C=C (Str.) bond conversion to saturated C-C bond via sulfur crosslinking and assign a C-S (Str.) bond [26-28] at 1134-1135 cm^{-1} and 669-701 cm^{-1} increased with increasing of curing time and curing temperature. It may be due to the added curing time and high curing temperature, which increase the reaction between sulfur and carbon double bonds [24-25].

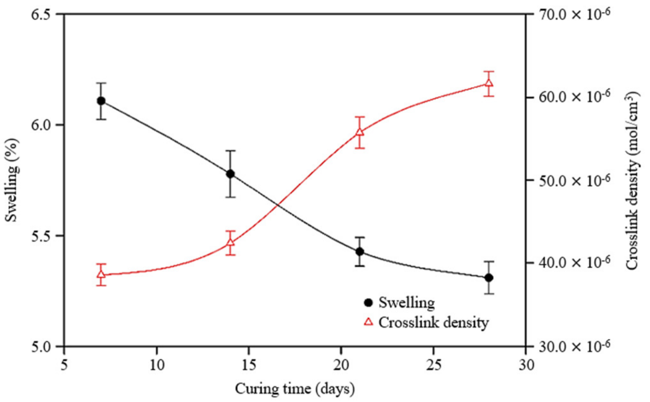


(a) FT-IR spectra of a self-repairing natural rubber sheet and the curing time

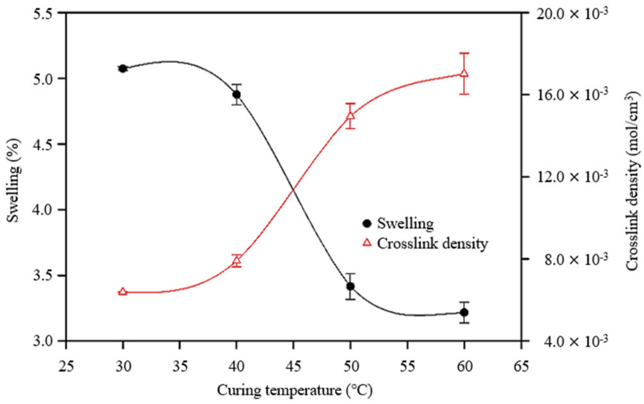
(b) FT-IR spectra of a self-repairing natural rubber sheet and the curing temperature

Fig. 7 FT-IR spectra of a self-repairing natural rubber sheet via the controlled crosslinking under the curing time and the curing temperature effect

The results indicated that the self-crosslinking of rubber sheets can continue with time and temperature changes. Moreover, the effect of curing time and curing temperature on crosslink density and swelling properties was studied. The rubber sheet's crosslinking density and swelling properties showed that the increasing curing time and curing temperature affected the crosslink density, and the swelling decreased (Figs. 8(a) and 8(b)). Because swelling properties are presented of crosslink density on the chemical structure of the rubber chain, the low swelling of rubber sheets indicates less mobility of rubber chain segments due to high crosslinking. On the other hand, a high swelling presents a low crosslinking that may be easily motion of rubber chain parts. Thus, the crosslink reaction of the natural rubber sheet to prepare the self-repairing rubber sheet as a surgical material pad prepared via the controlled curing time and curing temperature at room temperature is a new process and saved cost.



(a) Crosslink density and swelling properties of a self-repairing natural rubber sheet and the curing time



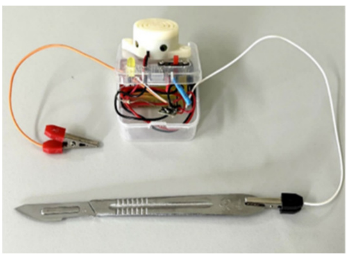
(b) Crosslink density and swelling properties of a self-repairing natural rubber sheet and the curing temperature

Fig. 8 Crosslink density and swelling properties of a self-repairing natural rubber sheet via the controlled crosslinking under the curing time and the curing temperature effect

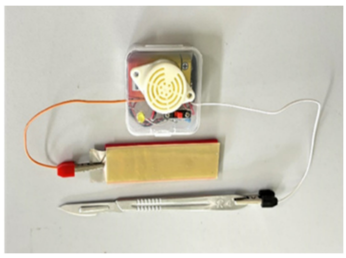
Table 1 The Δpeak intensity of rubber sheets at C-S (Str.) bond and C=C (Str.) bond using FT-IR

Curing time (days)	ΔPeak intensity (a.u.)			Curing temperature (°C)	ΔPeak intensity (a.u.)		
	C-S bond		C=C bond		C-S bond		C=C bond
	at 669-701 cm^{-1}	at 1134-1135 cm^{-1}	at 1662-1665 cm^{-1}		at 669-701 cm^{-1}	at 1134-1135 cm^{-1}	at 1662-1665 cm^{-1}
7	0.009	0.007	0.039	30	0.009	0.007	0.036
14	0.010	0.008	0.033	40	0.010	0.009	0.032
21	0.014	0.009	0.032	50	0.015	0.010	0.030
28	0.015	0.016	0.026	60	0.016	0.017	0.025

The self-repairing natural rubber sheet that was prepared under 30 °C was used on the electro-surgical training prototype, as shown in Fig. 9. The switch of the electro-surgical training prototype is on, and the surgical training pad used a self-repairing natural rubber sheet and connected the scalpel handle and an aluminum foil in layer 2 by using cable wire clips (crocodile).



(a) The electro-surgical training prototype

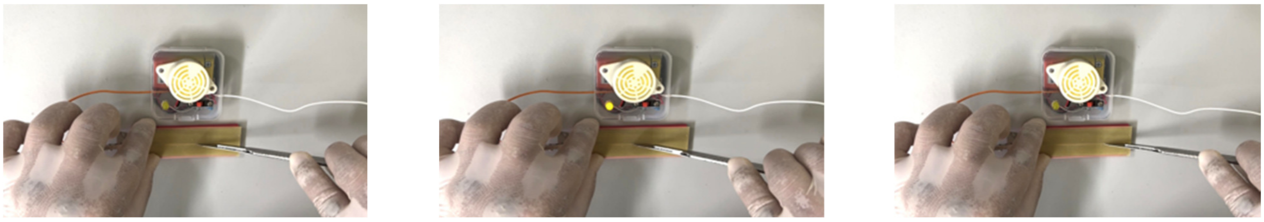


(b) A self-repairing natural rubber sheet as a surgical training pad

Fig. 9 The electro-surgical training prototype and a self-repairing natural rubber sheet as a surgical training pad

In step 1 (Fig. 10(a)), a rubber sheet was shear cut along the surface into two parts with a scalpel blade. Suppose the depth of the scalpel blade does not touch the aluminum foil. The buzzer and LED do not work (Table 2). Because electric current flows only in those circuits in a closed system, and the circuit is made by linking electrical components with wires. If the circuit is incomplete, current will not flow in the circuit. As a result, the circuit disconnected, and the LED and buzzer turned off.

Meanwhile, when the depth of the scalpel blade touches the aluminum foil (Table 2), an electrical circuit is fully connected to the component on the circuit board, which is electrons from a voltage or current source that can flow, and the electrical circuit works. The electrons must flow from the negative (-) to the positive (+) through a copper wire when electrons can flow through the wire. It leads to the activation of a buzzer audible and LED signal (Fig. 10(b)). The light of the LED and sound released from the buzzer continue to work, indicating the touching between the blade and the aluminum foil until the scalpel blade does not touch or remove the aluminum foil again. The LED and buzzer turn off (Fig. 10(c)). This testing showed that the electro-surgical prototype development used an electrical circuit. The prototype is a new device and is possible to be used for a basic medical lab to train surgical skills. It is easy to use, and all users can access it.



(a) The scalpel blade does not touch the aluminum foil and the buzzer and LED do not work

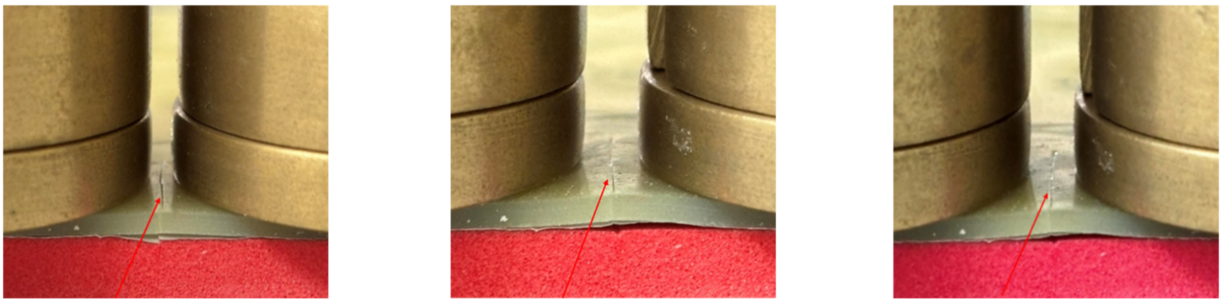
(b) The scalpel blade touches the aluminum foil and the buzzer and LED show signal

(c) The scalpel blade does not touch the aluminum foil and the buzzer and LED do not work

Fig. 10 The efficiency of the electro-surgical training prototype

Table 2 The efficiency work function of the electro-surgical training prototype

Depth of scalpel blade on the rubber sheet surface (mm)	Touching of scalpel blade and aluminum foil layer	Voltage (V)		Status	
		the buzzer	the LED	the buzzer	the LED
0.5	Not Touch	0	0	off	off
1.0	Not Touch	0	0	off	off
1.5	Not Touch	0	0	off	off
2.0	Not Touch	0	0	off	off
2.5	Touch	8.06	1.27	on	on



(a) The separate parts after the shear cut

(b) The adhesion between the touched inside surface of separate parts under self-repaired at 25-30 ℃ for 15 minutes

(c) The adhesion between the touched inside surface of separate parts under self-repaired at 25-30 ℃ for 15 minutes (different angle from 11(b))

Fig. 11 Photographs of the self-repairing natural rubber sheet under the compression force by weight (280 g)

In step 2 (Fig. 11(a)), the surgical training pad showed that the separate parts of the rubber sheet surface were operated and placed at 25-30 ℃ or room temperature for 15 min. Figs. 11(b)-(c) showed that weight (280 g) was placed side by side on the recovery of adhesion between the separate parts and presented the self-repairing natural rubber sheet did not tear at the adhesive of the shear cut position under tensile force on a rubber sheet surface by compression force (Fig. 12). The separate part decreased with self-repairing time increased as shown in Figs. 11 and 13. It confirmed the self-repairing of natural rubber sheets.

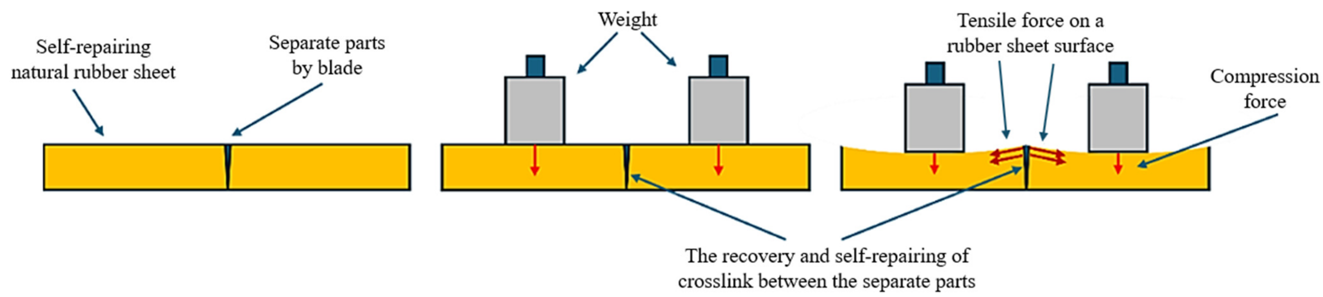
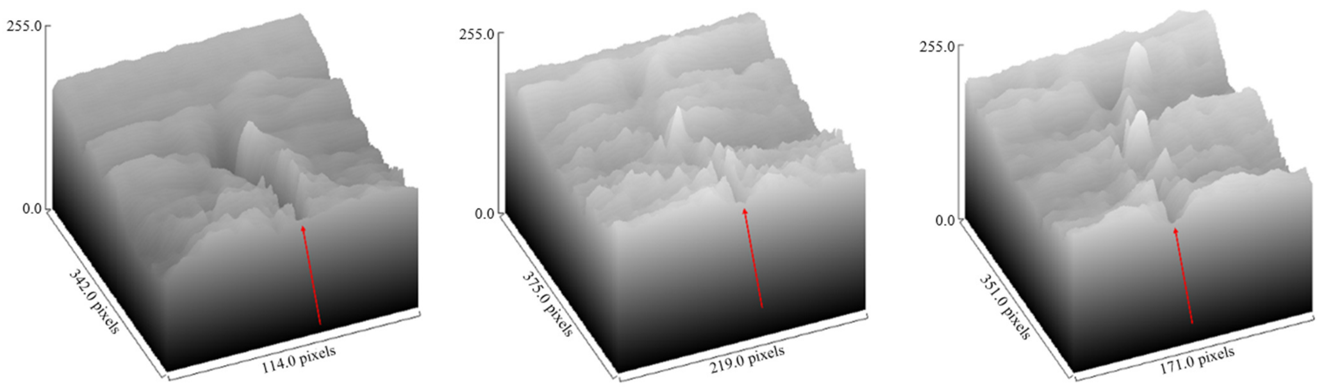


Fig. 12 The model explains the self-repairing natural rubber sheet did not tear at the adhesive of the separate parts under tensile force on a surface by compression force



(a) The separate parts after the shear cut

(b) The adhesion between the touched inside surface of separate parts under self-repaired at 25-30 °C for 15 minutes

(c) The adhesion between the touched inside surface of separate parts under self-repaired at 25-30 °C for 15 minutes (different angle from 13(b))

Fig. 13 Surface plotter mode of the self-repairing natural rubber sheet

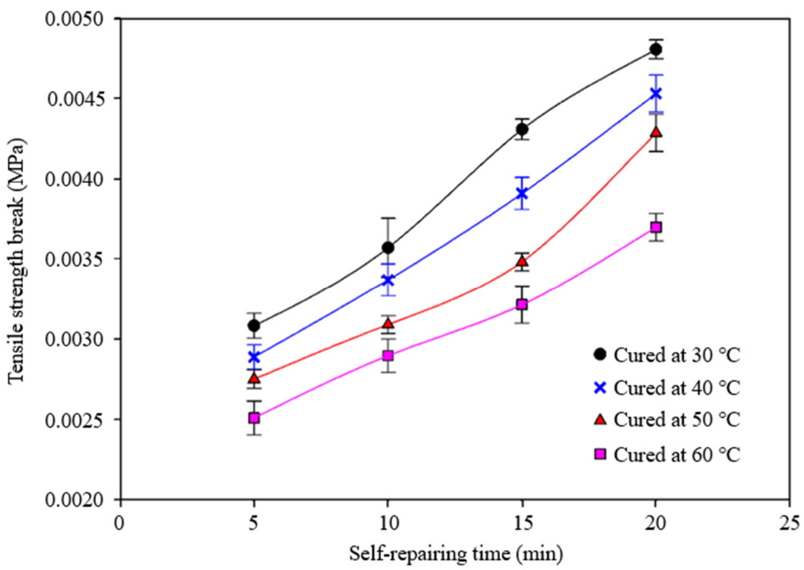


Fig. 14 Tensile strength at break and the self-repairing time at 25-30 °C of natural rubber sheet was cured at 30 °C (7 days), 40 °C (7 days), 50 °C (7 days), and 60 °C (7 days)

The self-repairing inside separated parts on the surface of natural rubber sheet occurred due to the reversible interactions of ionic crosslinks of natural rubber chains resulting from allowing the chain of natural rubber rearrangements [20, 29-30], which turns natural rubber into a self-repairing material at ambient temperatures [20, 29-30] that is improved and helped the adhesion between the segment of the touched inside surface of separate parts at uncured rubber chain segment via ionic crosslinks and then repaired via the recovery of adhesion between the separate parts and it affected on the tensile strength at break increased with the increasing of self-repairing time (Fig. 14) and the tensile strength at break of self-repairing natural rubber decreased with the curing temperature of rubber sheet increased (Fig. 14) due to high crosslink reaction of rubber chain, resulting in the uncured segment decreased.

Thus, the controlled crosslink process of a natural rubber sheet could be applied to prepare the self-repairing natural rubber pad. The self-repairing phenomena of natural rubber pads showed that they can be reused and possibly be repeatedly used as surgical material pads saving waste products to the environment when compared with other surgical material training. Thus, the controlled crosslinking can prepare a self-repairing natural rubber sheet that is interested in being used and replaced as a surgical training pad.

4. Conclusions

The self-repairing natural rubber sheet was prepared using a modified controlled crosslinking method. After that, the self-repairing properties were determined. It was found that increasing the curing time and temperature of vulcanization caused the crosslink density to increase and swelling properties to decrease. Meanwhile, the controlled crosslinking reaction of the rubber sheet was confirmed by FT-IR spectra. These spectra showed that the signal assigned at the C=C bond decreased and the C-S bond increased. The recovery of adhesion between the inside surface of cut parts via cutting using a scalpel blade on a natural rubber sheet occurred at the uncured segment of the rubber chain and, the tensile strength at break increased with the increasing self-repairing time. This indicates that the controlled crosslink method can prepare a self-repairing natural rubber sheet.

An electro-surgical training prototype was developed using a self-repairing natural rubber sheet for the surgical training pad. The electrical circuit prototype was tested and showed that when the switch is on. The scalpel blade's depth on the surgical training pad surface does not touch the aluminum foil, resulting in the buzzer and LED not working. In contrast, when the scalpel blade touches the aluminum foil, it leads to an electric current flowing through the circuit board, activating the buzzer and LED. The electro-surgical training prototype with self-repairing natural rubber with a surgical training pad is a new piece of equipment that medical lab students can use. The prototype can be easily built as a small device with a simple circuit. It costs 5 USD, and the self-repairing natural rubber sheet costs 1 USD per 20 pieces. In addition, another advantage of self-repairing natural rubber is that it can be repeatedly used as a surgical material pad and can be formed in many shapes such as arms, ears, and heart. Thus, the prototype can be widely used in many surgical practices and is easy to access.

Conflicts of Interest

The authors declare no conflict of interest.

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