Proceedings of ASME 2020
International Mechanical Congress and Exposition
IMECE 2020
November 16-19, 2020, Portland, OR, USA

IMECE2020-24341

INFLUENCE OF COMPOSITE POLYMER COATINGS ON THE INSERTION FORCE OF NEEDLE-LIKE STRUCTURE IN SOFT MATERIALS

Kavi I Patel, Long Zhu, Sai Teja Reddy Gidde, Fei Ren, Parsaoran Hutapea
Department of Mechanical Engineering, Temple University
1947 N 12th Street, Philadelphia, Pennsylvania, USA

ABSTRACT

This study is aimed to evaluate the effects of coated surgical needles with composite polymers such as polydopamine (PDA), polytetrafluoroethylene (PTFE), and carbon. The coated needle's lubrication properties were measured using 3 DOF force sensors and 3D robot system by the repetitive insertion in soft tissue materials. Needle durability is a measure of needle sharpness after repeated passage through high stiffness tissue materials. The composite coatings were shown to reduce the insertion force by ~49% and retraction forces by ~46% when tested using a bovine kidney. The surface roughness and the lateral friction force of the needle are measured using the Atomic Force Microscope (AFM). The adhesion energy of the different coating on the needle will be measured using a nano-scratch method.

INTRODUCTION

The medical surgeons generally use surgical needles for disease diagnoses such as biopsy, brachytherapy, thermal ablation, and drug delivery. The biomechanical performance of the needle is mainly based on the needle properties such as lubrication (or low surface roughness), ductility, sharpness, the geometry of the tip, and the method of insertion. The sharpness of the needle can be evaluated from the magnitude of penetration force encountered by the tip of the needle. Needles with smaller gauge sizes are becoming widespread for their capacity to reduce the pain associated with needle insertion. Insulin needles, dental needles, microneedles are examples of fine needles used for personal and clinical uses. When the larger diameter needle is inserted into human organs, it first punctures the skin. After puncturing the skin, the needle will travel into the tissue where the friction force on the interface of the needle and tissue dominates the mechanics of the insertion (Figure 1). In addition to the friction force, the pressure from the tissue on the needle and the cutting force influence the insertion force. Tissue damage is often caused by friction and cutting forces during needle insertion [1-3].

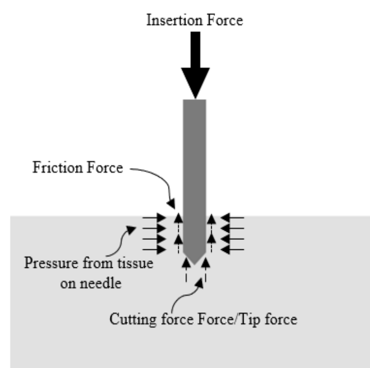


FIGURE 1: THE FORCES ACTING ON NEEDLE DURING INSERTION IN THE TISSUE

In previous studies, coating medical devices with polymers have shown some potential with the limitations [4]. In various studies, the surface of medical needles were coated with silicone lubricants [5], diamond-like carbon [6], metallic glass [7], polytetrafluoroethylene; to reduce the friction and thereby to reduce the amount of the force required for insertion. However, the effectiveness of these coatings decreases with use, especially when used for the suturing of the skin.

PTFE has useful properties such as a low coefficient of friction, hydrophobicity, biocompatibility, and chemical resistance. However, PTFE has a non-stick property which makes its coating less durable and it can be easily detached from surfaces under frictional load and shear. This is where Polydopamine comes into play to overcome these shortcomings. Polydopamine (PDA) polymer has a unique property of the adhesion. Polydopamine can adhere to any organic and inorganic surfaces, meaning that PDA can be used as a mechanism of the adhesion between substrate and materials that are typically adhesion resistant. This study aims to combine the strong adhesion between PDA and PTFE with the inclusion of an activated carbon filler to produce highly durable PTFE composite coatings with exceptionally low surface roughness and coefficients of friction (COF).

MATERIALS AND METHODS

Two different types of coating conditions were investigated in this study: (I) Stainless steel needle coated with PDA (basecoat) and PTFE (topcoat), (II) Stainless steel needle coated with PDA (basecoat) and PTFE + Carbon (topcoat). The needle used in this study has a diameter of 16 gauge and a length of 10 cm.

The 50 mM PDA solution (PH 8.5) was prepared using dopamine hydrochloride (H8502, Sigma Aldrich, St. Louis, MO, USA) and tris (hydroxymethyl) aminomethane (T1503, Sigma Aldrich, St. Louis, MO, USA). Before the polydopamine-coating deposition onto the needles, needles were clean to remove any surface impurity. Steel needles were submerged into the PDA solution for a duration of 24 h to grow the thin coating of PDA on needle interface [8,9]. Then needles were removed and rinsed in DI water prior to the deposition of PTFE and PTFE + Carbon topcoat.

PTFE (Disp 30 DuPont Fuel cell earth, Woburn, MA) solution was directly used in the dip coating machine to coat the needle with PTFE. After rinsing PDA coated needles with DI water, they were placed into the fixture of the dip-coating machine. PDA coated needles were dipped into PTFE solution at the speed of 10 mm/min and kept for 3 min in the PTFE solution to form a PTFE coating on PDA coated needle. After that, Needles were extracted at the same speed of 10 mm/min. Then, PDA and PTFE coated needles were placed in the oven for drying at the 120^{o}C. Afterwards, Needles were transferred to the furnace, where needles were heated up to 373^{o}C to remove water particles and the wetting agent from the coating.

For the PTFE and carbon coating, the solution was prepared with 25% Carbon in PTFE. PDA coated needles were dipped into PTFE and carbon solution at the speed of 10 mm/min and kept for 3 min in the PTFE and Carbon solution to form the coating on PDA coated needle. After that, Needles were extracted at the same speed of 10 mm/min. Then, coated needles were placed in the oven for drying at the 120^{o}C. Afterward, Needles were transferred to the furnace where needles were heated up to 373^{o}C to remove water particles and the wetting agent from the coating [9,10,11]. This process typically produces 1-3 µm of a thin coating. The surface roughness study was performed by AFM under non-contact tapping mode and contact mode respectively [12].

In this study, we build the 3-DOF robot with the linear actuator and motors. The combination of motors and linear actuators gives us decent control over movements in 3D space and the speed with the precise needle maneuvering (Figure 2) [13].

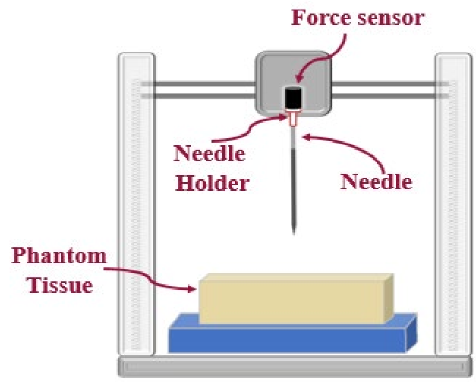


FIGURE 2: EXPERIMENTAL TEST SETUP

We used 6 DOF force/torque sensor (Nano17® ATI Industrial Automation, Apex, NC), which can measure the forces in millinewtons. Needle fixture is attached to the force sensor to measure the forces exerted on the needle. Initial experiments and analysis of data were performed to obtain a better understating of force data. Three groups of experiments were conducted with five PDA and PTFE coated; five PDA and PTFE+ Carbon; and five bare needles respectively on the bovine kidney. The bovine has the stiffness of ~ 4-5 kPa. We performed five insertions and extractions with each needle. The test setup is programmed to perform insertions and extractions every two cm with a speed of 5 mm/sec. In the first row, experiments were performed with the bare needles. After performing five insertions in a straight line, the second row of insertions was started approximately two cm perpendicular to the first-row insertion with the PDA and PTFE coated needles. The insertions with the PDA and PTFE + Carbon coated needles were performed with the same pattern in the third row.

RESULTS

We used force sensors to measure all forces and atomic force microscope (AFM) to measure the surface roughness. Figure 3 shows the results of polymer-coated needles average force data vs the depth upon experiments of the bovine kidney. The upper region of the data shows the average insertion force and another region down to it shows the average extraction forces. The maximum average force for uncoated needle was 3.54 N, PDA and PTFE coated needle was 2.71 N and for PDA and PTFE+ activated carbon was 1.82 N. From the Figure 3 A, it is interpreted that the average insertion force reduction in PDA, PTFE + activated Carbon is approximately 49 % than the bare needle. The standard deviations for average forces are shown in figure 3 B.

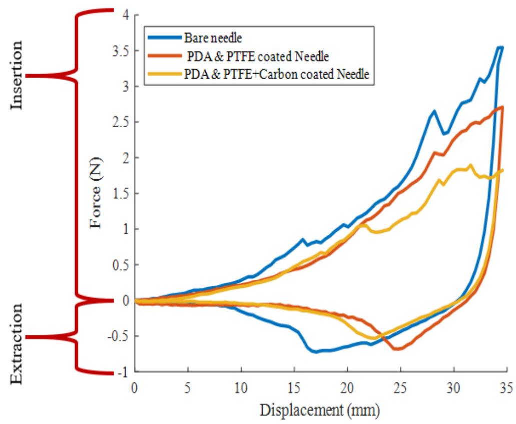


FIGURE 3 A: AVERAGE FORCE AND DEPTH GRAPH FOR BARE NEEDLE, PDA AND PTFE COATED NEEDLE AND PDA AND PTFE + CARBON COATED NEEDLE UPON INSERTION INTO BOVINE KIDNEY

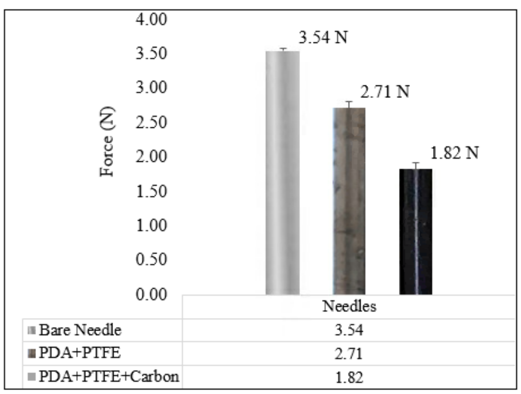
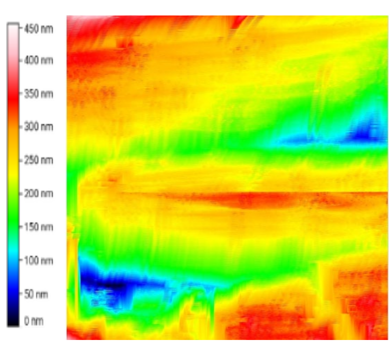
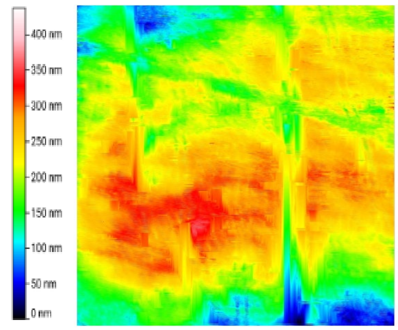


FIGURE 3 B: MAXIMUM FORCE AND STANDARD DEVIATION DATA OF BARE NEEDLE, PDA + PTFE NEEDLE AND PDA+ (PTFE AND CARBON COATED NEEDLE) UPON INSERTION INTO BOVINE KIDNEY.



(A)



(B)

FIGURE 4 (A) AFM SCAN OF BARE NEEDLE. (B) AFM SCAN OF PDA+PTFE+C COATED NEEDLE

After the AFM analysis, we found that the PDA - PTFE - Carbon coating surface roughness root means square value (RMS) is reduced by ~ 50 % compared to the bare needle's surface roughness root mean square value. RMS roughness value for the PDA+PTFE +C needle is around ~52 nm while bare needle RMS roughness value is ~102 nm (Figure 4). The study of the adhesion force/energy of the coating on stainless steel needle will be performed using the nano-scratch mode of nanoindenter (Hysitron TI980) [14].

CONCLUSION

The results indicate that the addition of 25% Carbon particles in the PDA/PTFE films significantly reduces the surface roughness, insertion forces, and enhance the nonstick property of the surface. The composite coatings were shown to reduce the insertion force by ~49% and retraction forces by ~46%. This shows great promises for not only surgical needles but also for the other medical devices where the high friction is the challenge. The analysis of Sterilization, biocompatibility, coefficient of friction, and durability will be our future work.

ACKNOWLEDGEMENTS

The authors would like to acknowledge National Science Foundation (CMMI Award #1917711) and Temple's Center of Excellence in Traumatic Brain Injury Research for their financial support.

REFERENCES

[1] Okamura AM, Simone C, O'Leary MD, "Force modeling for needle insertion into soft tissue," *IEEE Transactions on Biomedical Engineering*, 15(1), pp. 1707-1716, 2004.

[2] Cheng Z, Chauhan M, Davies BL, Caldwell DG, Mattos LS, "Modelling needle forces during insertion into soft tissue," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society,*

EMBS, pp. 4840-4844, 2015.
[3] Abolhassani N, Patel R, Moallem M, “Needle insertion into soft tissue: A survey,” *Medical Engineering and Physics*, 29(4), pp. 413-431, 2007.
[4] Ching HA, Choudhury D, Nine MJ, Abu Osman, NA, “Effects of surface coating on reducing friction and wear of orthopedic implants,” *Science and Technology of Advanced Materials,* 15(1), 014402, 2014.
[5] McClung W, “Enhancing needle durability by silicone coating of surgical needles,” *Journal of Emergency Medicine*, 13(4), pp. 515-18, 1995.
[6] Dearnaley G, Arps JH, “Biomedical applications of diamond-like carbon (DLC) coatings: A review,” *Surface and Coatings Technology*, 200(7), pp. 2518-2524, 2005.
[7] Chu JP, Yu CC, Tanatsugu Y, Yasuzawa M, Shen YL, “Non-stick syringe needles: Beneficial effects of thin film metallic glass coating”, *Scientific Reports*, 6, 31847, 2016.
[8] Foust SA, “Ultrathin PTFE Coating for Hypodermic Needles Enabled by Mussel-Inspired PDA Adhesive Layer”, 2014.
[9] Beckford S, Mathurin L, Chen J, Fleming RA, Zou M, “The effects of polydopamine coated Cu nanoparticles on the tribological properties of polydopamine/PTFE coatings,” *Tribology International*, 103, pp. 87-94 2016.
[10] Beckford S, Cai J, Fleming RA, Zou M, “The Effects of Graphite Filler on the Tribological Properties of Polydopamine/PTFE Coatings,” *Tribology Letters*, 64(3), 42, 2016.
[11] Crisp DJ, Walker G, Young GA, Yule AB, “Adhesion and substrate choice in mussels and barnacles,” *Journal of Colloid and Interface Science*, 104(1), pp. 40-50, 1985.
[12] Quereda J, Castellanos-Gomez A, Agraït N, Rubio-Bollinger G, “Single-layer MoS2 roughness and sliding friction quenching by interaction with atomically flat substrates,” *Applied Physics Letters*, 105(5), 053111, 2014.
[13] Patel KI, Gidde STR, Li H, Podder TK, Ren F, Hutapea P, “Insertion force of polydopamine-coated needle on phantom tissues,” *2019 Design of Medical Devices Conference, ASME Digital Collection,* DMD2019-3271*,* 2019.
[14] Das S, Lahiri D, Lee DY, Agarwal A, Choi W, “Measurements of the adhesion energy of graphene to metallic substrates,” *Carbon,* 59, pp. 121-129, 2013.