Development of graphene-based end-of-life sensors for fire-protective fabrics

Patricia I. Dolez[1], Hyun-Joong Chung[2], Jane Batcheller[1], Chungyeon Cho[2], Diana Yehia[1], Lelin Zheng[1,2], Christina A. Braun[1,2], Reza Khalkhali[2], Zhitong Lin[2], Ashok Chhetry[2], Ankit Saha[2], Md. Saiful Hoque[1], Marwa Khemir[2], Nadeesha Samaraweera[1]*

[1] Department of Human Ecology, University of Alberta, Edmonton, Canada
[2] Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Canada
* Corresponding author pdolez@ualberta.ca

Keywords
fire-protective fabrics, end-of-life sensors, firefighter protective clothing, degradation, graphene.

Introduction

The protective clothing industry and workers at risk of exposure to heat and flame can rely on some high performance materials developed over the last fifty years to provide the protection needed while allowing some level of comfort. This includes a series of inherently thermal- and fire-resistant fibres such as para- and meta-aramids. However, if these materials exhibit exceptional performance when new, the various conditions they are exposed to during the lifetime of the clothing will reduce their performance over time (1). In addition, these large losses in performance may occur before any sign of damage is visible to the naked eye (2). Finally, the current increase in the laundering frequency of the protective clothing resulting from the discovery that smoke particles and combustion-generated carcinogenic chemicals can penetrate firefighters' protective clothing (3), will make obsolete the current retirement directives.

To tackle this critical issue, a graphene-based textile end-of-life sensor has been developed to allow monitoring the condition of the fire-protective clothing over its lifetime. The sensor will be stitched at a few strategic locations on the fire-protective clothing. The residual conductivity of the sensor will be measured using a simple multimeter as part of the regular assessment that firefighters and other workers at risk of heat and flame exposure are required to do of their protective equipment. Based on the values measured, they will be warned if their protective clothing has experienced a level of exposure to aging conditions that may have decreased its performance below the safe range and thus needs to be replaced.

Methods

The strategy used for the development of this end-of-life sensor relies on polymers that are sensitive to the same aging conditions as high performance fibres, i.e. heat, UV, and moisture (4). These polymers are combined with a graphene-based conductive track. Upon reaching a certain level of exposure to one of these aging agents sufficient to cause the fire-protective fabric to enter an unsafe range, the sacrificial polymer degrades, causing a disruption in the graphene conductive track and a change in its electrical conductivity. As illustrated on Fig 1, the UV-, heat- and moisture-sensitive components of the end-of-life sensor are secured on a fabric substrate that will be stitched as a patch at a few strategic locations on the firefighter protective clothing.

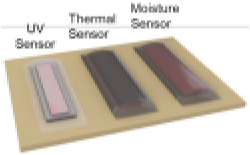

Figure 1. End-of-life sensor with the UV-, thermal- and moisture-sensitive components on the fabric substrate.

Figure 2. Picture of a thermal sensor prototype

Results and discussion

A picture of a thermal sensor prototype is shown in Figure 2. The sacrificial polymer selected for the thermal sensor is polyetherimide (PEI) as its activation energy upon thermal aging based on ultimate tensile strength data was shown to match that of fire-protective fabrics used as outer shell in firefighter protective clothing (5). In addition, the formation of cracks was observed at the surface of the PEI film as a result of aging, which would create a disruption of the graphene layer on the PEI film. This graphene layer was successfully prepared on PEI using laser engraving (4). The thermal sensor (Figure 2) also includes contacts so that the graphene residual electrical conductivity can be measured using a multimeter. The sensor is covered by an encapsulation layer; it has been shown to resist laundering, repeated bending, and abrasion (6).

In the case of the moisture-sensitive sensor component, polyimide was selected as the sacrificial polymer: its activation energy upon hydrothermal aging based on ultimate tensile strength data is similar to that of fire-protective fabrics used as outer shell in firefighter protective clothing (7). In addition, it becomes brittle upon water immersion in hot water. It also allows the formation of the graphene layer by laser engraving.

In terms of the UV-sensitive sensor component, a 2-pack polyurethane exposed to UV aging displayed the same trend in the variation of the tensile toughness retention as a function of aging time as fire-protective fabrics used as outer shell in firefighter protective clothing that were exposed to the same conditions (8). In addition, blisters were observed to form at the surface of the 2-pack polyurethane upon UV aging.

An appropriate fiber content for the end-of-life sensor fabric substrate has also been identified so that the fabric substrate does not interfere with the operation of the sensor (9). A blend of 93% meta-aramid, 5% para-aramid, and 2% carbon fibers (Nomex® IIIA) was shown to resist thermal and hydrothermal aging as well as laundering much better than the fabrics typically used as outer shell in firefighter protective clothing. On the other hand, it has a larger sensitivity of UV aging, which will be corrected with a UV-protective finish.

With all the different materials and manufacturing technologies now identified for the graphene-based end-of-life sensor for fire-protective fabrics, the next step is the scale-up to industry-scale production. This work is underway in partnership with the company Davey Textile Solutions, which has taken on to bringing the end-of-life sensor to the market (10). This company, which manufactures high visibility reflective trims, including for fire-protective clothing, has the production capacity to manufacture the graphene-based end-of-life sensors for the different steps of weaving, finishing, laser engraving, lamination, and product assembly.

Conclusions

Firefighters risk their lives every day to protect ours. Their protective clothing is critical to allow them performing their duties while remaining safe. Yet, the performance of their protective clothing degrades over time as it is exposed to high heat, UV light, moisture, laundering, etc., which raises serious concerns for their safety. A graphene-based end-of-life sensor for fire-protective fabrics has been developed to solve this issue. It is now moving towards commercialization with the company Davey Textile Solutions.

Acknowledgements

This research has been funded by NSERC and MITACS (Canada). The authors also wish to thank Anna Bonatto, Jemma Forgie, Ajibola Anifowose, and Maya Thabal-Herron for their contribution to the project.

References

1. McQuerry M, Klausing S, Cotterill D, Easter E. A post-use evaluation of turnout gear using NFPA 1971 standard on protective ensembles for structural fire fighting and NFPA 1851 on selection, care and maintenance. Fire Technol. 2015;51(5):1149-66.
2. Rossi RM, Bolli W, Stampfli R. Performance of firefighters' protective clothing after heat exposure. Int. J. Occup. Saf. Ergon. 2008;14(1):55-60.
3. Keir JLA, Akhtar US, Matschke DMJ, Kirkham TL, Chan HM, Ayotte P, et al. Elevated exposures to polycyclic aromatic hydrocarbons and other organic mutagens in Ottawa firefighters participating in emergency, on-shift fire suppression. Environ. Sci. Technol. 2017;51(21):12745-55.
4. Dolez P, Chung H-J, Cho C. End-of-life sensors for fabrics. PCT International Patent Application PCT/CA2022/000006. 2022/03/03.
5. Cho C, Nam SL, de la Mata AP, Harynuk JJ, Elias AL, Chung H-J, Dolez PI. Investigation of the accelerated thermal aging behavior of polyetherimide and lifetime prediction at elevated temperature. J Appl Polym Sci. 2022;139(15):51955.
6. Chhetry A, Dolez PI, Chung HJ. Development of high temperature polymer-based end-of-life wearable sensors for fire-protective textiles. Canadian Chemical Engineering Conference (CCEC 2022), October 23 - 26, 2022; Vancouver, BC, Canada.
7. Braun CA, Nam SL, de la Mata AP, Harynuk J, Chung H-J, Dolez PI. Hydrothermal aging of polyimide film. J Appl Polym Sci. 2022;139(20):52183.
8. Khemir M, Dolez PI, Chung HJ. UV aging of polyurethane films and its application as a sacrificial layer for an end-of-life sensor for fire-protective fabrics. Faculty of Engineering Graduate Research Symposium (FEGRS 2022), November 8-10, 2022; Edmonton, AB, Canada.
9. Yehia D. Investigation of support fabrics for graphene-based end-of-life sensors for fire protective garments. M. Sc. Thesis. Edmonton, AB, Canada: University of Alberta; 2021.
10. Yehia D, Lawson L, King D, Chung H-J, Batcheller J, Dolez PI. Towards commercialization of graphene-based end-of-life sensors for fire-protective fabrics. 8th Edition of the International Conference on Intelligent Textiles and Mass Customisation (ITMC 2022), Sept 19-21, 2022; Montréal, QC, Canada.