Research and Creative Experience for Undergraduates Program (RCEU) Summer 2021

Smart Nails for Lithium-ion Battery Internal Short Circuit and Thermal Runaway Characterization

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Introduction

Lithium-ion batteries that are widely used in various applications may catch fire due to thermal runaway, a chain of uncontrolled exothermic reactions. As schematically shown in Fig.1, internal short circuit (ISC) is a main cause of thermal runaway, during which very high current flows through the ISC location. Our group recently reported a slow, small and *in situ* sensing nail penetration method to trigger ISC and understand how the ISC leads to thermal runaway [1]. However, the nail developed in that research had an asymmetric tip that distanced the temperature-sensing location from the ISC location and was not strong enough to penetrate thick lithium-ion batteries. Built on the previous research, this project aims to develop smart nails that are strong and have a symmetric tip.

Experimental

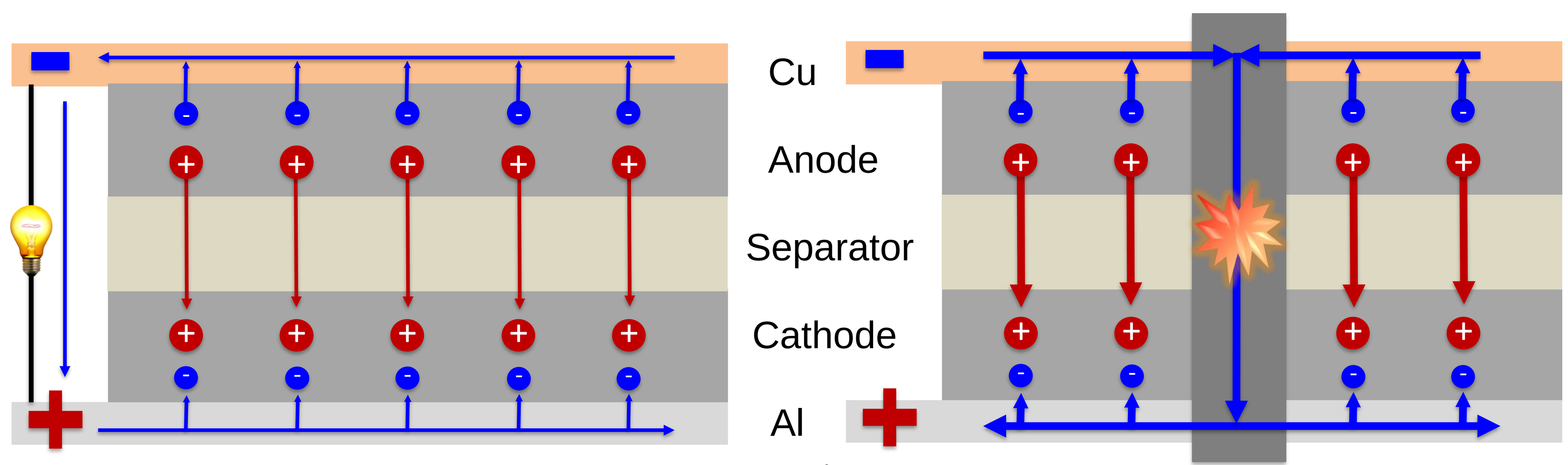
As shown in Fig.2, four smart nails were designed and fabricated in this project. Nail 1 was the first design to be sharpened symmetrically to 60° and consisted of brass and stainless steel. The thermocouple was imbedded so that its tip was flush with the nail tip. Nail 2 was made similarly but exclusively from stainless steel and with an extended thermocouple for increased sharpness. Nail 3 was designed to lower heat transfer through the nail while maintaining the same tip as Nail 1. Its tip was made with the same stacked layers, but only the outer layer continued for the entire length of the nail. The empty space in the nail body was filled with J.B. Weld epoxy (8265S). Nail 4 was similar to Nail 2 but had a larger diameter for increased strength and reduced ISC resistance. It also had thermal insulation around the nail/holder connection to protect the holder. Additionally, its diameter, material, and length were comparable to industry standard solid nails used in nail penetration tests without *in situ* diagnosis. All the four nails were tested on fully charged 3-Ah pouch format lithium-ion cells using a similar protocol as that in our group's previous work [1]. The nail penetration speed was ~0.03 mm/s. Cell voltage, tab voltages, cell surface temperature and nail tip temperature were measured at 5 Hz.

Results

Fig.3 shows testing results with the nails developed in this project. Time 0 was defined to be the moment cell voltage dropped. Several interesting phenomena were observed. First, all the nails were successful in triggering thermal runaway and capturing temperature at the ISC locations. Second, all the nail tip temperatures reached a peak quickly but then dropped before increasing again. The temporary temperature drop could be caused by aluminum current collector breakage [1], cell swelling changing the temperature measurement location, or by cooling effects of electrolyte evaporation or separator melting. Further work is needed to determine the exact cause. Third, the cell voltage dropped rapidly in all the tests as expected, but surprisingly the voltage dropped below 0 V during the tests with Nail 3 and Nail 4. It is currently unknown why this happened and further work is necessary. Note that during Nail 1 test the cell surface temperature was much lower than that in other tests because the thermocouple was detached from the cell surface during thermal runaway. The nail tip temperature during Nail 1 test increased slower and less than that in other tests, which could be because the thermocouple was flush with the nail tip instead of slightly protruding. In addition, during the Nail 3 test it was observed that the J.B. weld epoxy used in this project could not withstand the high temperature during thermal runaway, but thermal insulation could address the issue.

Conclusion

A process was developed for designing and fabricating smart nails with symmetric tips and enhanced strength for characterization of lithium-ion battery ISC and thermal runaway. Four nails made in this project successfully triggered ISC and thermal runaway of 3-Ah pouch-format lithium-ion battery cells and captured nail tip temperatures. Further work is needed to explain the experimental results, especially the phenomena of temporary nail tip temperature drop after the first peak in all tests and the negative cell voltage during Nail 3 and Nail 4 tests. Additionally, the limitations of J.B. Weld epoxy and the benefits of a protruding thermocouple were observed which could be used for development of next generation smart nails.



$$anode: \mathrm{LiC_6} \rightarrow Li^+ + e^- + 6C$$
$$cathode: 2Li_{0.5}CoO_2 + Li^+ + e^- \rightarrow 2\mathrm{LiCoO_2}$$

Fig. 1 Schematic of current flows in Li-ion cells during normal discharge and ISC triggered by nail penetration

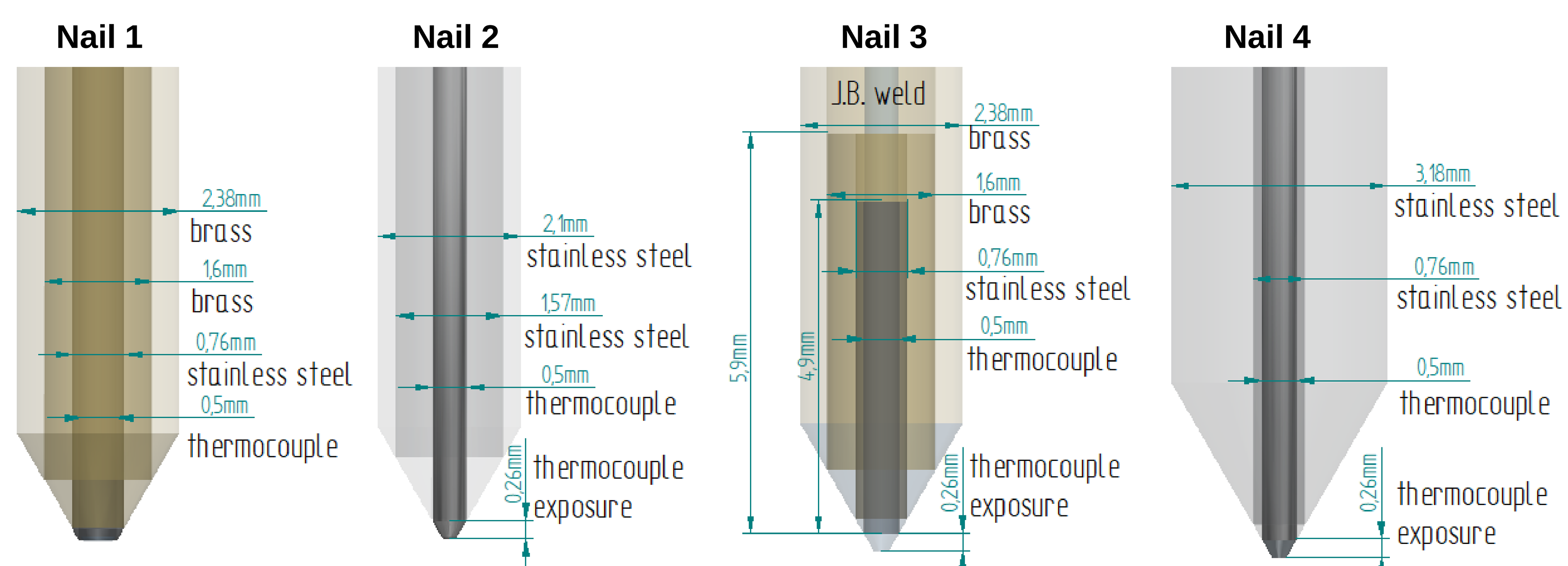


Fig. 2 Schematics of smart nails developed in this project

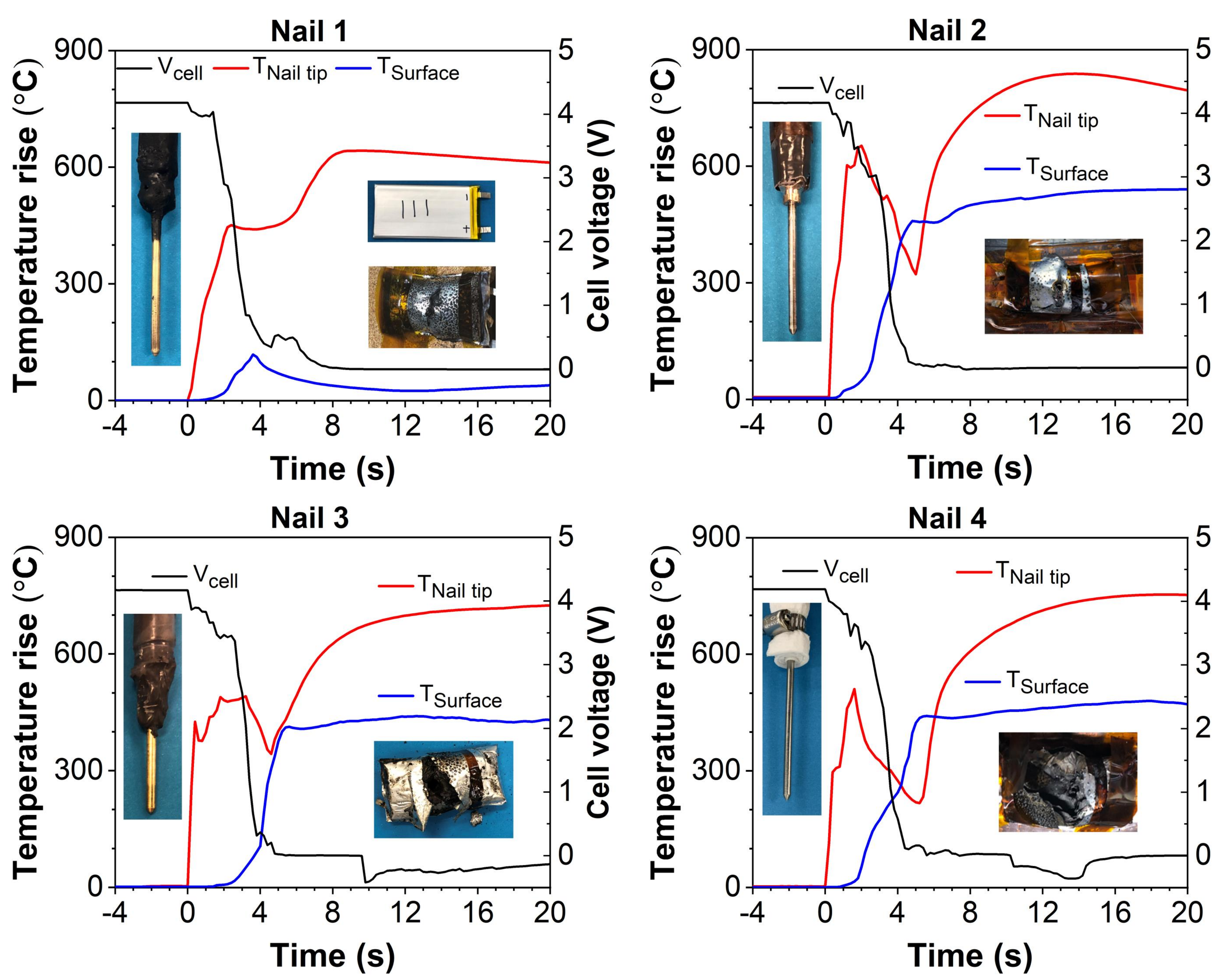


Fig. 3 Testing results of 3-Ah lithium-ion battery cells using the four nails developed in this project

Acknowledgements

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Reference

1. Shan Huang *et al* 2020 *J. Electrochem. Soc.* 167 090526

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