BODY ARMOUR WITH POWER STORAGE CAPABILITIES

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***Abstract*—Adding shear thickening fluid (STF) into ballistic fabrics to create "liquid body armour" to improve kinetic impact resistance has been proven. Here, for the first time, we have tried to turn "liquid body armour" into a battery system which is not only able to supply power, but also to provide protection against bullet impacts. Such multifunctional energy storage systems can share space and weight with existing body armour. Batteries with different combinations of Kevlar-based electrodes, Kevlar separator and shear thickening electrolytes have been assembled and their electrochemical performance was investigated. They demonstrated reasonable charge/discharge capacities. The concept of a kinetic impact resistant battery, combination of Kevlar electrodes with Kevlar separator, or Kevlar separator with STF electrolyte, has been demonstrated. However, some technical issues such as the moisture retained inside the Kevlar electrodes need to be addressed in order to improve the performance.**

Keywords—battery; shear thickening fluid; Kevlar fabric; protection, lithium ion batteries

I. INTRODUCTION

The protection of individual combatants against the effects of an adversary's weapon systems has been a critical consideration of a military force for as long as humans have engaged in combat. From the most rudimentary hand held shields to block kinetic impact, to highly sophisticated offensive and defensive systems that protect against advanced technological threats, individual combatants are now afforded significant protection, but it comes at a cost of increased physical burden.

One area of increasing physical burden is in batteries to store electrical energy. Power systems carried by an individual combatant are becoming more demanding in terms of quantity and it is now a critical risk in the design of modern integrated soldier combat ensembles (SCE). It is therefore an advantage if components of a SCE are designed to perform more than one function. The development of shear thickening fluids (STF) battery offers potential to reduce the total number of systems carried by an individual combatant by combining the protective nature of body armour components and the storage of electrical energy. Significant research is being undertaken within DST Group in this area [1-3] under Land Division's *Osiris* program.

Here we report a battery whose configuration is identical to "liquid body armour". Two basic components of "liquid body armour" were used to assemble the battery. Kevlar was coated with active materials to form the electrodes, or was used as the separator and STF as the electrolyte. The ultimate goal is to create a ballistic battery that can not only share the space but also the weight of existing body armour, in order to improve the safety of batteries as well as lessen the burdens of the military personnel. This paper presents the results of work to develop materials that offer the potential of safe storage of energy, combined with an element of protection against kinetic threats. The novel lithium ion batteries were fabricated with either a combination of Kevlar electrodes with Kevlar separator, or a Kevlar separator with an STF electrolyte, and their electrochemical performances were evaluated.

With further development, the body armour may serve as a battery as well, thus eliminating the need for carriage of additional (heavy) external batteries. Such power supply devices would facilitate the development of other cutting-edge technologies, such as TALOS (Tactical Assault Light Operator Suit), a battery-powered robotic exoskeleton designed to protect the lives of soldiers in the front lines for practical use, as the weakest aspect of TALOS is that users are required to carry substantial numbers of batteries.

II. BACKGROUND

Battery safety issues have received significant attention [4] especially in the military field. To date, most of the work on battery mechanical safety has focused on external packaging. Namely, the traditional solution to this problem is adding external protection packages, which was a disadvantage of heavy weight. Using solid electrolyte, solid polymer electrolyte or ionic liquids to replace the commonly used flammable liquid organic electrolytes is another solution to create wearable lithium ion batteries. However, such electrolytes normally suffer from low ionic conductivity, leading to inferior performance, particularly at high current drains. In addition, they cannot provide protection against physical impacts.

As demonstrated by our previous work [1-3], we have developed a new strategy to improve battery safety as well as maintain their performance by introducing smart fluids properties into electrolytes. These electrolytes not only show higher ionic conductivities but also exhibit the shear thickening effect under pressure or impact. Shear thickening electrolytes have also been further investigated and considered as one of the most promising methods of ensuring safety in Lithium ion batteries [5-7].

STFs are an example of a non-Newtonian fluid, often termed as a dilatant fluid. At low shear rates, this fluid has low viscosity, acts as a lubricant and flows easily. However, upon impact, the fluid adopts a rigid-like state due to a rapid increase in viscosity and thus becomes less penetrable. Recently, this type of material has attracted attention in developing smart materials and composites [8-10] as their unique material properties make them ideal for many applications, such as shock absorption [11], damping [12], and ballistic protection and stab resistance (liquid body armour) [13-19].

Adding STF into ballistic fabrics to generate "liquid body armour" has sparked significant attention, as it can improve the kinetic resistance of fabrics with more flexibility. A significant amount of research has been conducted on liquid body armour at the same areal density as conventional ballistic and stab resistant solution [13-19]. For example, a study conducted by the United States Army Research Laboratory showed that four layers of Kevlar impregnated with STF could dissipate the same amount of energy as 14 layers of neat Kevlar. Treating four layers of neat Kevlar with STF only increases its mass by 2.9 g and its thickness by 0.1 mm [13]. In general, "liquid body armour" composed of saturated Kevlar can be much thinner, lighter and more flexible than conventional neat Kevlar whilst simultaneously preserving the wearer's safety. STF also reduces the trauma resulting from kinetic impacts due to its increased energy dissipation capacity.

III. EXPERIMENTAL SETUP

A. Materials

Kevlar fabric was provided by Colan Australia with an areal density of 318 g/m^2. Fumed silica particles, lithium hexafluorophosphate ($LiPF_6$), ethylene carbonate (EC, $C_3H_4O_3$) and diethyl carbonate (DEC, $C_5H_{10}O_3$) were sourced from Sigma-Aldrich.

B. Conductive Coating/Plating of Kevlar Fabric

The Kevlar fabric was pre-treated with acetone then rinsed thoroughly with deionized water, and dried for use. Prior to a silver nanowire (AgNW) coating, an oxygen plasma treatment was applied to the Kevlar fabric for ~3 min on each side to improve the surface hydrophilicity. The fabric was then immersed into a silver nanowire (diameter, 120 nm; length, 20 µm) isopropanol (IPA) suspension (4 mg/mL) for 1 hour at room temperature, and then dried at 70°C for 30 min. This process was repeated several times to increase the silver nanowire uptake. For the silver plating process, the fabric was firstly sensitised in a solution containing 5 g/L $SnCl_2$ and 0.06 M HCl at room temperature for 1 h and then rinsed with water. The sensitized fabric was soaked into a silver plating solution containing 3 mg/mL $AgNO_3$, 6.25 wt% $NH_3{\cdot}H_2O$ and 0.008 g/mL NaOH. After a quick addition of 2.6 g/L glucose solution, the dynamic chemical reaction occurred. The reaction was kept at 40°C for 40 min. The colour of the fabric was changed from brown at the early stage and then to metallic silver at the later stage of the process.

C. *Preparation of Kevlar based Cathode and Anode, and STF Electrolyte*

The cathode and anode were made by utilising the doctor blade technique of coating active material slurry onto the conductive Kevlar substrate. For the cathode, the active material slurry was prepared by mixing $LiFePO_4$/carbon black/PVDF (polyvinylidene difluoride) (weight ratio, 75:15:10) in N-Methyl-2-pyrrolidone (NMP). For the anode, the slurry consisted of graphite/carbon black/PVDF (8:1:1) in NMP. The hot plate temperature was set to 80°C.

The conventional organic liquid electrolyte used was 1 M $LiPF_6$ in a mixture of ethylene carbonate (EC) and diethyl carbonate (DEC) (1:1, v/v). The STF was prepared by mixing fume silica particles with the conventional electrolyte. The added amount of SiO_2 was 6.3 wt%.

D. Battery Assembly

Coin cell batteries (2032 type) were assembled using different combinations of electrode, electrolyte and separator. The cathode material was $LiFePO_4$ (LFP), and anode material was either graphite or lithium foil. The cathode and anode electrodes were separated by a conventional battery separator or Kevlar fabric, and then filled with the electrolyte $LiPF_6$ in EC/DEC or STF. The commercially available cathode $LiFePO_4$ on Al foil and anode graphite on Cu foil were also investigated and referred to as conventional electrodes in this work. These cells were assembled in an argon-filled glovebox (MBrau, UNIlab Plus).

E. Battery charge/discharge testing

The electrochemical performance of these batteries was investigated. Galvanostatic charge/discharge tests were conducted using a LAND CT2001A battery test system.

IV. RESULTS AND DISCUSSIONS

A. Preparation of Kevlar fabric electrodes

In a battery system, the electrode consists of active materials on a substrate. The substrate functions as a mechanical support as well as a current collector facilitating electron transport. Thus a highly conductive substrate is required. Kevlar is an insulator.

Turning non-conductive Kevlar into an electronically conductive material was the first step to fabricate a Kevlar based electrode. Silver layer was applied with a silver nanowire suspension in isopropanol or plated on the Kevlar fabric based on the method described above [20]. The Kevlar fabric changed colour from yellow to grey and finally metallic silver during the coating process (Fig. 1a). The resistance of these two fabrics were decreased to several ohms, and the silver plated fabric demonstrated a much higher conductivity (Fig. 1a). Such highly conductive Kevlar can readily ensure a steady electron flow. The loading mass of silver coating was ~2.5 mg cm^{-2} from the electroless plating, and 2.1-3.2 mg cm^{-2} after the coating using silver nanowires. The cathode and anode were made by doctor blade coating active material slurry onto the conductive Kevlar fabric substrate with a mass loading of ~2 mg cm^{-2} for the cathode and ~1 mg cm^{-2} for the anode. Fig. 1 shows the photos of the resulting conductive Kevlar fabrics and a schematic illustration of the doctor blade coating process used to coat conductive Kevlar fabric.

B. Battery assembly and electrochemical performance

In this study, different types of batteries were assembled with Kevlar based electrodes, Kevlar separator and STF electrolytes to investigate the impact of variations of these components on the battery performance. Coin cell batteries (Fig. 2a) were assembled and investigated in this work.

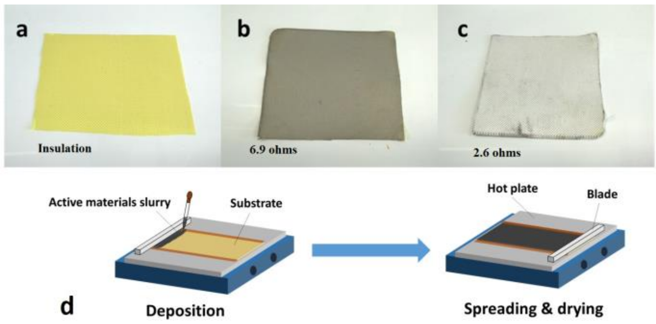

Fig. 1. (a-c), Photos of Kevlar fabric (a), AgNW coated (b) and silver plated (c) Kevlar fabric; (d), Schematic illustration of a doctor blade coating process.

The functioning of Kevlar fabric as a separator and STF as an electrolyte were first investigated in the cell with commercial electrodes. It can be seen that the cell with commercial separator in a liquid electrolyte delivered a capacity of 110-120 mAh/g at all the applied current densities (20, 50, 100 mA/g). No significant capacity drop at higher current densities can be observed, indicating good rate capability (Fig. 2b). With Kevlar fabric as a separator the cells showed similar behaviour, similar capacities as well as good rate performance (Fig. 2c). Using the combination of Kevlar separator and STF electrolyte the cell showed slightly lower discharge capacities at all applied current densities than those using commercial electrolyte (Fig. 2d). These results clearly demonstrate that Kevlar fabric can be used as separator in lithium ion batteries, and the Kevlar-STF combination worked very efficiently as well.

The Kevlar electrodes were firstly investigated in a half-cell (e.g., coupled with a Li foil) using liquid electrolyte and a conventional separator; the commercial electrodes were used as control (Fig. 3). The LFP coated Kevlar fabric electrode displayed a discharge plateau at ~3.4 V and a discharge capacity of 95 mAh g^{-1} at a current density of 20 mA g^{-1}, which was slightly lower than that 119 mAh g^{-1} from the commercial LFP electrode on an Al foil with a similar discharge plateau (Figure 3a, c). For the anode, the graphite coated Kevlar fabric electrode delivered a discharge capacity

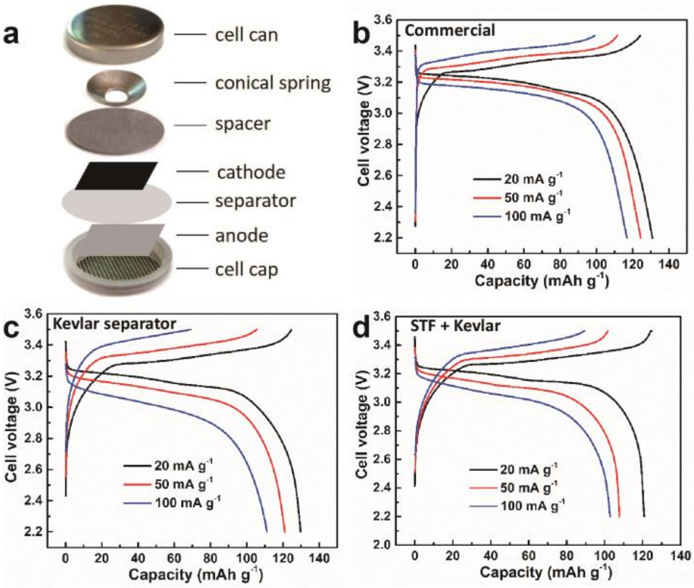

Fig. 2 (a) Configuration of a coin cell; Charge/discharge curves of the cells with conventional electrodes in liquid electrolyte with commercial separator (b), Kevlar separator (c); the combination of Kevlar separator and STF (d).

of 312 mAh g^{-1} at 50 mA g^{-1}, which was slightly lower than that from a commercial graphite electrode on a Cu foil (330 mAh g^{-1}; Fig. 3b, d). These results clearly demonstrate that the Kevlar electrodes offer an electrochemical performance close to that of commercial electrodes. The slighter lower discharge capacity might be ascribed to the higher resistance of the fabric substrate compared to a metal substrate. Increasing the amount as well the uniformity of silver coating on the fabric may solve the problem.

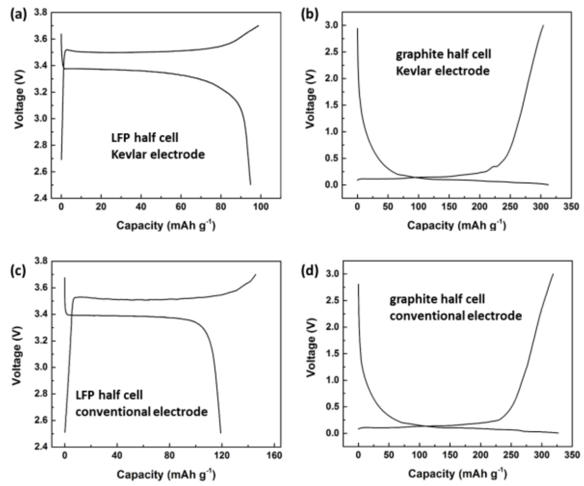

Fig. 3 Charge-discharge curves of a half-cell using an LFP coated Kevlar electrode at 20 mA g^{-1} (a), or a graphite coated Kevlar electrode at 50 mA g^{-1} (b); Charge-discharge curves of commercial LFP electrode (c); and graphite electrode (d) as control.

The Kevlar electrodes were also further investigated in full cells. The charge-discharge curves of those full cells with Kevlar electrodes are shown in Fig. 4. The battery (Fig. 4a) composed of Kevlar electrodes and Kevlar separator delivered a capacity of 31 mAh g^{-1} at a current density of 20 mA g^{-1}, evidencing the functioning of this type of battery. Even when the Kevlar separator was replaced with a commercial separator, the battery (Fig. 4b) still delivered a low capacity of 28 mAh g^{-1}. The reason for such lower capacities may be due to the electrolyte decomposition related to retained moisture inside the Kevlar electrodes.

Kevlar as a separator or the Kevlar separator-STF combination in a full cell with commercial electrodes (Fig. 2), the effective functioning of Kevlar electrodes in a half cell (Fig. 3) have been demonstrated. Battery performance can be further improved by optimizing the battery assembly process.

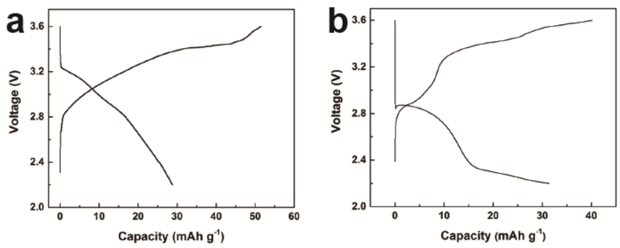

Fig. 4. Charge-discharge curves of a cell composed of Kevlar electrodes and Kevlar separator (a), and a cell with Kevlar electrodes and conventional separator (b), in liquid electrolyte at a current density of 20 mA g^{-1}.

V. CONCLUSIONS

The lithium ion batteries fabricated with either a combination of Kevlar electrodes with Kevlar separator, or a Kevlar separator with an STF electrolyte, has been demonstrated. Kevlar electrodes with an active material coating afford comparable performance to commercial electrodes. Battery systems composed of conventional electrodes with a Kevlar fabric separator in commercial electrolyte, or the combination of a Kevlar fabric separator and an STF electrolyte all offer electrochemical performance very close to that of a conventional battery system. These results clearly demonstrate the potential usage of Kevlar electrodes, Kevlar separators, and STF electrolyte in lithium ion batteries. However, the moisture retained inside the Kevlar textile has a significant impact on battery performance, which causes a severe problem of electrolyte decomposition, especially with Kevlar electrodes in a full cell system. Removing moisture from the electrodes, the fabric separator and electrolyte is essential for utilising their full potential as performance batteries. Our future goals involve optimizing the fabrication process of a soft-packed battery based on shear thickening fluids and ballistic fabric, and evaluating its performance against a range of kinetic impacts.

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