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Electrically Conductive Flame Sprayed Aluminum Coatings on Textile Substrates

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In this study, electrically conductive and flexible aluminum coatings using powder and wire flame spraying were successfully deposited onto diverse textiles. The influences of various process parameters and fabric materials on the electrical conductivity and microstructure of the metal-fabric composites were investigated. Preliminary results show that to obtain excellent coating surface conductivity values a specific coating quantity of higher than 20 mg/cm^2 is required. After further optimization of the spraying parameters, very good specific surface conductivities (~500 S_A) could be obtained even with reduced coating quantities. Through an adequate parameter optimization a reduction in the specific coating quantity was also achieved while high conductivity values were retained. In addition, when the coating quantity was reduced, the flexibility of the fabric substrates was better conserved. This investigation illustrates that optimized electrically conductive composites with flexible fabric substrates can be produced without any preliminary thermal or chemical fabric specifications.

Keywords composite materials, flame spray, influence of spray parameters

1. Introduction

Electrically conductive flexible fabric materials represent a new approach for the production of various integrated applications, e.g., wearable electronics, lighting, or communication in medical techniques (Ref 1-3).

To produce composite materials based on copper and textiles, chemical processes are presently being used. However, these techniques have two significant disadvantages: they are expensive and they are potentially dangerous for the environment because they consist of immersing the part to be covered into acid or basic electrolytes. Other physical processes, such as CVD, are high-temperature processes that can significantly overheat the fabric substrate. Furthermore, these processes produce only very thin coatings, which are barely conductive when applied to textiles. Therefore, due to the above-mentioned limitations for the chemical and physical processes, thin metallic copper sheets are usually used to produce such composites. However, these sheets are liable to crease and tear. Currently no process exists for the manufacture of sufficiently conductive aluminum-fabric materials composites.

For this study, the flame spray process was chosen to produce aluminum-coated fabric composites. The main advantages of this process are its low operational cost and its versatility, which can easily be scaled up for mass production (Ref 4). The use of two different flame spray processes (powder and wire) enables a comparison of the influence of the feedstock materials on the composites properties.

The combination of the high particle temperatures involved in the flame spraying of metallic materials and the extremely high heat sensitivity of the fabrics represents an interesting challenge in the production of such metal-textile composites. To protect the fabrics while spraying metallic materials onto them, an adequate cooling system must be developed, which does not cause physical damages to the textile.

2. Materials, Coatings, and Experimental Procedure

Two existing conventional flame spray gun apparatus were used for this study: a Metco 5P-II powder gun and a GTV-12E wire gun. Conventional aluminum powder ($-90+45$ µm) and aluminum wire (Ø 3.2 mm) were used throughout this work; details are reported in Ref 5. The powder mostly consists of blocky particles without undesired sharp edges, resulting in reasonable flowability without significant pulses.

Three different polyester fabrics, labeled 5248, 5911, and "XX" were used. Fabrics 5248 and 5911 are similar,

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except that 5911s structure is much looser, making its density (fibers/cm^2) lower than that of 5248. Fabric 5911 also has two significantly different rough sides. The third fabric, labeled "XX," has an even more open mesh structure combined with an uniform side structure. The properties of the different textiles are described elsewhere (Ref 5).

For the first optimization step, standard flame spray parameters for aluminum were used. These spray parameters were described in a previous work (Ref 5). In this first optimization procedure, only the standoff distance and the substrate cooling were varied for different amounts of deposited materials. For the experiments without any substrate cooling, the standard standoff distance for powder and wire spraying was chosen. Afterward, for the optimization of the process parameters, an adequate substrate cooling system was used, which enabled a standoff distance reduction of 250 mm for the powder flame process and of 300 mm for the wire process from the standard spray distance value. These reduced distances in conjunction with the use of the cooling system did not induce any thermal damage to the textile substrates (Ref 5). The A4-sized fabric substrates were coated using conventional gun movements, parallel to the substrate surface, using a 6-axis ABB robot.

The coating quantity (mg Al/cm^2 fabric) of the sprayed samples was determined by weighing the fabric samples before and after the spraying process and dividing this weight by the area of the sprayed sample.

The electrical surface conductivity of the sprayed samples was determined via a 4-point measurement method with a Keithley 2010 multimeter. The detailed electrical surface conductivity measurement procedure was documented previously (Ref 5). The conductivity measurement errors as well as the spread in the data were estimated to be 10% of the measured value.

A scanning electronic microscope (SEM) was used to investigate the surface and the microstructure of the coatings as well as the interface between the coatings and the fabrics. For the microstructure and interface investigations, the samples were embedded and cross sections were prepared using standard metallographic procedures.

3. Results and Discussion

For the first experiments performed in this study, coatings were produced with standard spraying parameters without any cooling system and without any optimization to identify the value of the coating quantity at which the surface conductivity had a value higher than 0 S_A, and this value was determined to be 20 mg/cm^2. Based on these results, to save material and time, it was decided to use a coating quantity of 20-25 mg/cm^2 as the target value for further experiments, where the spraying parameters were optimized. Figure 1 shows the electrical conductivity values as a function of the coating quantity for fabrics 5248 and 5911 for the first series of experiments, where no substrate cooling was deployed.

Samples produced using fabric 5248 possess a higher surface conductivity than do those based on fabric 5911. This is assumed to be due to a better interconnection between the individual sprayed splats for fabric 5248, which has a tightly woven structure, compared to fabric 5911, which has a more three-dimensional and looser structure. In addition, independent of the fabrics used, using of wires as raw materials produces samples with higher surface conductivity than the powder sprayed samples. This is believed to be due to the higher kinetic energy and more uniform melting of the particles involved in the wire flame spray process (Ref 6). The surface morphology of the samples produced onto the 5248 fabric using powder or wire as raw material is shown in Fig. 2 and 3. As a first observation, it is obvious that their microstructures consist of individual particles with a large number of nonmolten or partially molten particles. This is impressive since these samples, particularly the wire sprayed sample, possess a relatively good electrical conductivity.

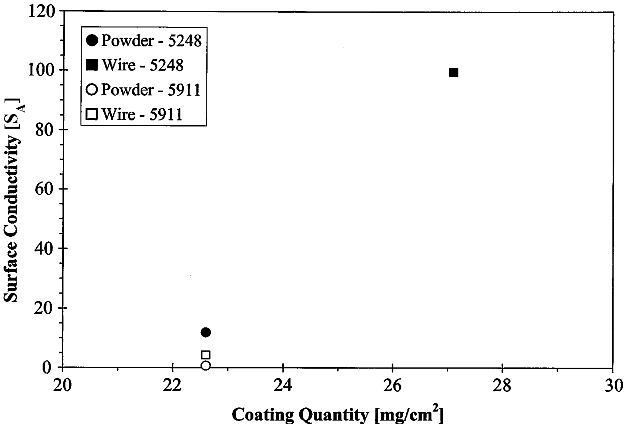

Fig. 1 Electrical conductivity as a function of the Al coating quantity for fabrics 5248 and 5911 using powder and wire as raw materials and without substrate cooling

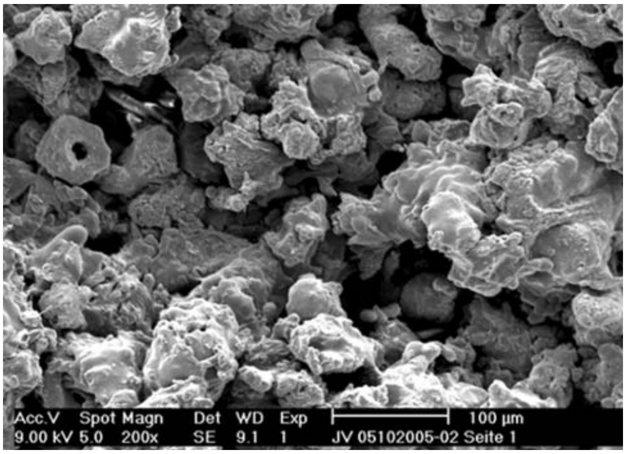

Fig. 2 Morphology of the surface of the Al powder sprayed polyester 5248 without substrate cooling

Therefore, it may be concluded that even if only limited contacts and interconnections between the individual splats exist, a relatively good absolute sample surface conductivity may be achieved. Cross sections of the samples indicate that penetration of aluminum into the fabric thickness is minimal (Ref 5).

The second series of experiments were performed using two air amplifiers to cool the 5911 fabric surface during the spraying process. The 5911 fabric was chosen because of its three-dimensional structure, which improved the surface conductivity with optimized spray parameters, and also because the initial conductivity was extremely low (see Fig. 1), rendering increases in the conductivity value easily observable. As expected, substrate cooling made it possible to decrease the standoff distance significantly, as shown in Fig. 4 for the powder and in Fig. 5 for the wire as raw material. In these figures, the standoff distance value 0, hereafter called SDP or SDW (SDP: standard distance for powder; SDW: standard distance for wire), represents the standard distance without substrate cooling. The other distances are shorter than this standard distance by the values indicated. It is worth noting that for the results shown in Fig. 4 and 5, the coating quantity ranged between 23 and 32 mg/cm^2 (Ref 5). Apart from producing sprayed fabric samples without causing thermal damages, the reduced standoff distance generated by using an adequate cooling system has a significant influence on the electrical conductivity as well as on the microstructure of the aluminum coatings, as shown in Fig. 6-8. It is obvious that using an adequate cooling system allows to significantly reduce the standoff distance, resulting in an increase in the surface electrical conductivity without inducing any damage on the fabrics. The fabrics were visually observed after the spray process to identify the presence or the absence of any thermal damage. This was afterward completed by observations of the cross-sections of the samples using SEM.

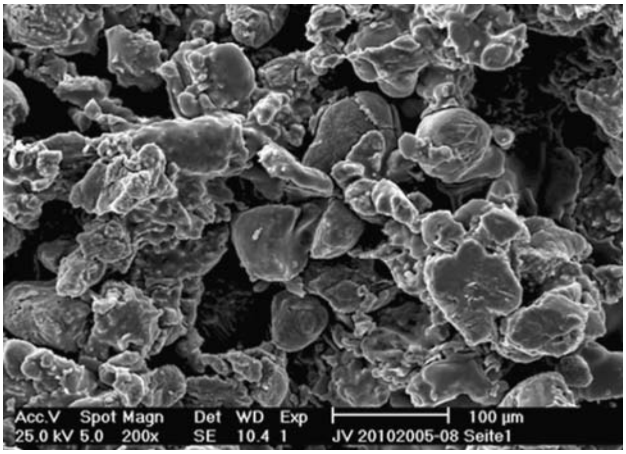

Fig. 3 Morphology of the surface of the Al wire sprayed polyester 5248 without substrate cooling

For the powder sprayed samples with comparable coating quantities, the increase in surface conductivity with reduced spray distance is assumed to be due to a more uniform and better molten particle state on impact with the fabric surface. The optimum standoff distance was defined as the distance that gave the best surface conductivity without inducing any fabric damages and is equal to SDP-200 mm for the powder spray process.

For the wire sprayed samples, the optimal standoff distance is SDW-300 mm; at shorter distances (SDW-350 mm), the electrical conductivity is significantly reduced and the fabrics were damaged.

The standoff distance was further reduced for the wire sprayed (<SDW-350) and for the powder sprayed samples (<SDW-200), but these shorter distances induced either enormous damages on the fabrics for the shortest distances (easily seen by the naked eye) or light damages, which were sometimes only visible by microscopy. The surfaces of samples SDP-200 and SDW-300 are shown in Fig. 6 and 7 and their cross sections in Fig. 8. It is clearly visible that the textile fibers are completely covered on both sides of the fabric and the coatings consist of better

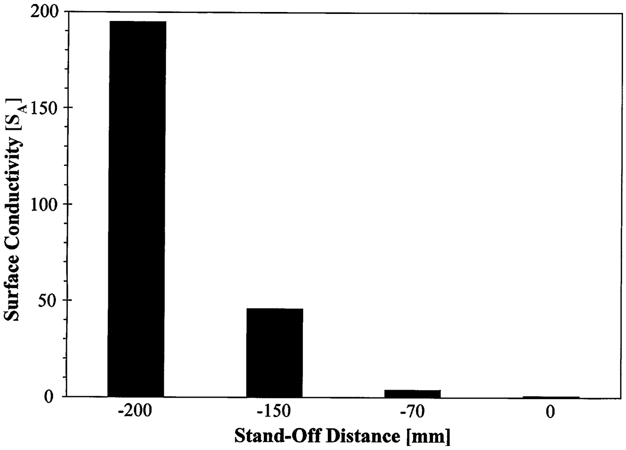

Fig. 4 Results of the standoff distance optimization using substrate cooling, fabric 5911, and powder as raw material

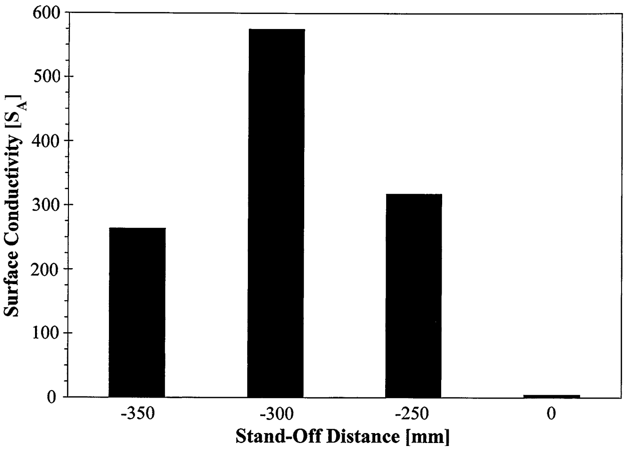

Fig. 5 Results of the standoff distance optimization using substrate cooling, fabric 5911, and wire as raw material

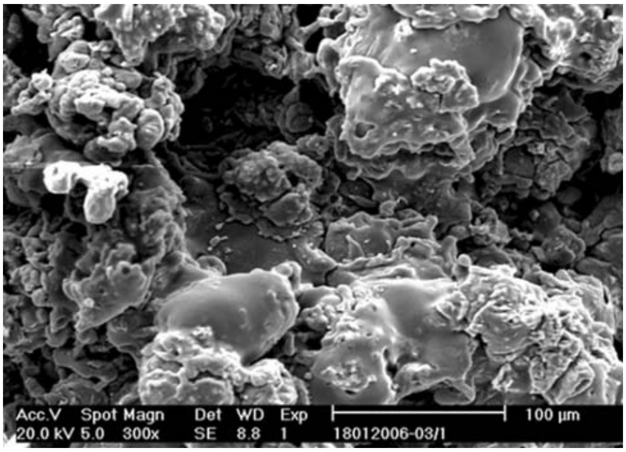

Fig. 6 Morphology of the surface of the Al powder sprayed polyester 5911 with substrate cooling at a standoff distance of SDP-200 mm

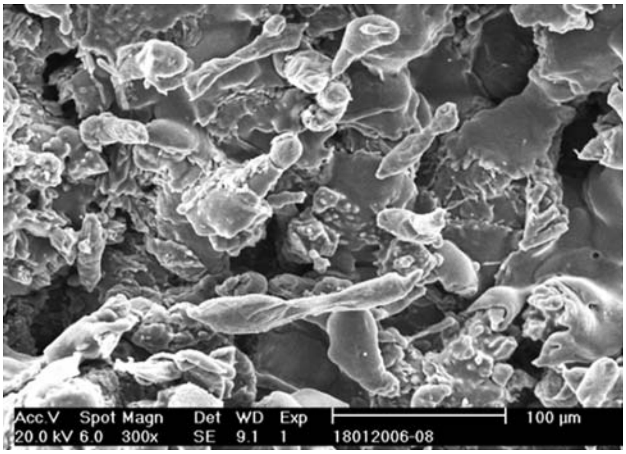

Fig. 7 Morphology of the surface of the Al wire sprayed polyester 5911 with substrate cooling at a standoff distance of SDW-300 mm

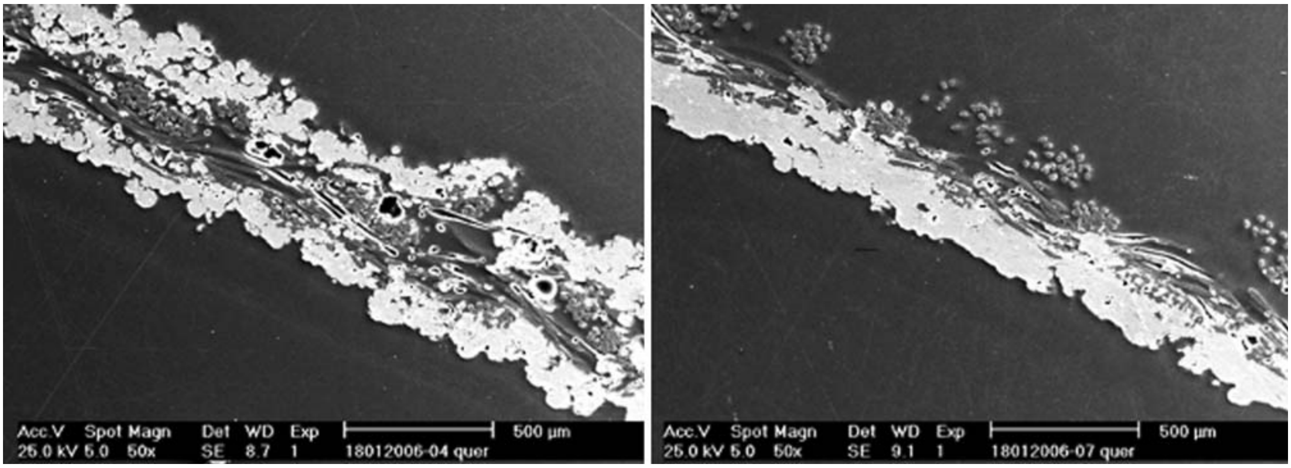

Fig. 8 Cross sections of the Al powder sprayed (left, sample SDP-200 mm, double-sided) and Al wire sprayed (right, sample SDW-300 mm) polyester 5911 using the optimal standoff distance and with substrate cooling

molten spray particles, which is better than when no cooling was used. For the wire sprayed sample (SDW-300 mm), an excellent and uniform aluminum distribution with surface electrical conductivity values of up to 500 S_A was obtained, as shown in Fig. 7. The coating microstructure is independent of the fabric side used, as shown by the cross sections of the double-sided sample SDP-200 mm in Fig. 8(a), but some cavities are present in the center of the fabric material and contacts between the two Al coatings may be observed at only a few locations. Through the wire spray process, the SDW-300 mm coating is considerably flatter and more uniform, showing a very good interconnected structure, as shown in Fig. 8(b).

The fabric structure has a significant influence on the electrical conductivity of the samples, as shown in Fig. 9 and 10. For a fixed coating quantity, smooth fabric sides possess higher surface electrical conductivity values than rough fabric sides, which is believed to be due to their lower specific surface values. This influence is only significant for the wire sprayed samples. It was also observed that more open fabric structures induce higher surface electrical conductivity values, due to the metallic contact between each coated side of the fabric material (see Fig. 10). A thin, light composite with a surface conductivity value interesting for the desired application (which is described later in this paper) using a dense fabric structure with an Al coating quantity of 13 mg/cm^2 is shown in Fig. 11.

An interesting application of electrically conductive aluminum coatings deposited onto polyester fabric materials is their deployment as positive electrodes in lithium-ion batteries. Figure 12 shows the typical structure of such a battery.

The replacement of the aluminum foil through an aluminum-coated fabric material as well as the copper foil through a copper-coated textile has several advantages in a battery structure, as shown in Fig. 12. Through the intrinsically three-dimensional structure of the fabric

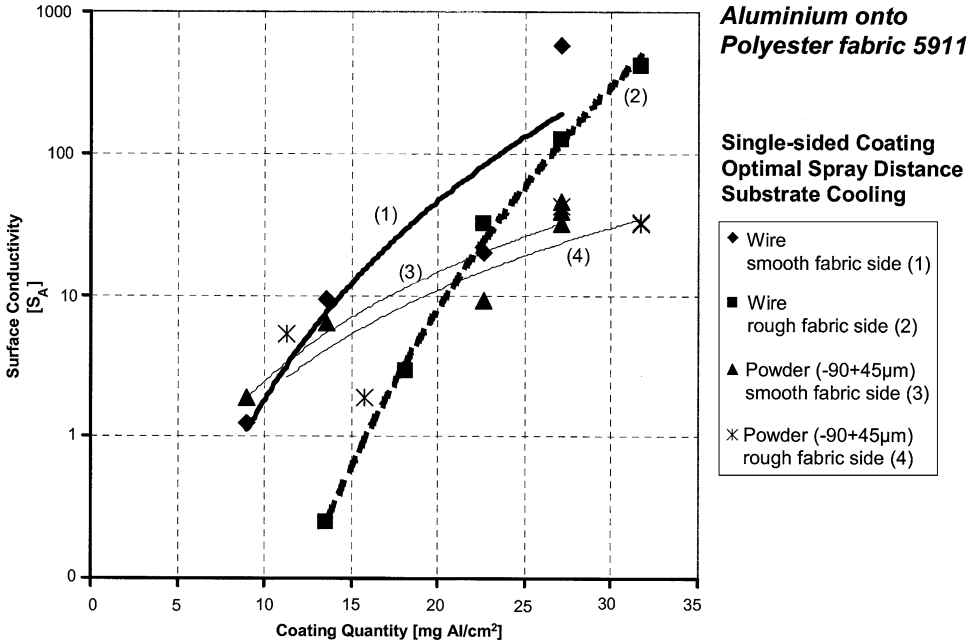

Fig. 9 Relationship between the coating quantity and the surface conductivity of aluminum-coated fabric sides and the influence of the smooth or rough textile side

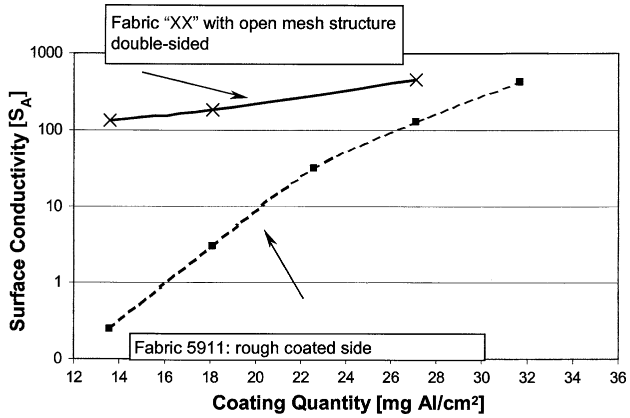

Fig. 10 Relationship between the coating quantity and the surface conductivity of aluminum-coated fabric sides: Influence of a dense textile structure in comparison to an open structure in double-sided coated fabric materials

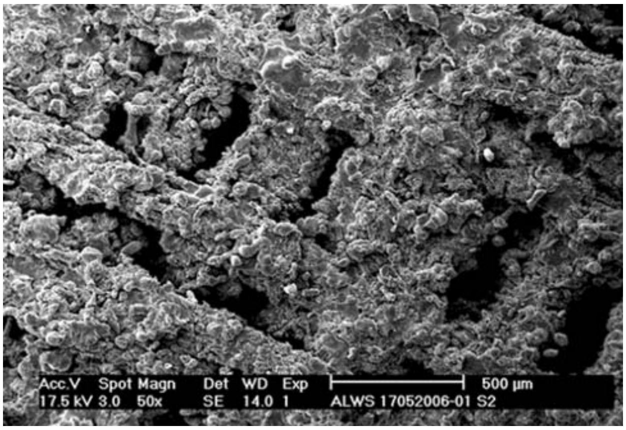

Fig. 11 Morphology of the surface of an Al wire sprayed double-sided “XX” polyester fabric using the optimal standoff distance (13 mg Al/cm^2 per side)

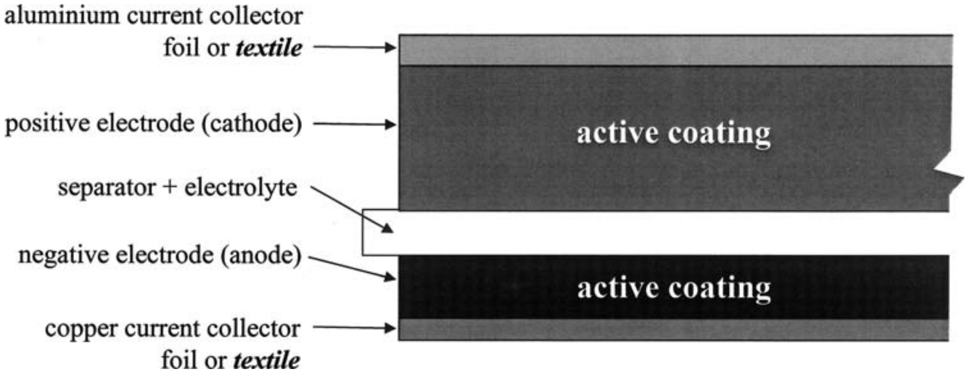

Fig. 12 Schematic setup of a lithium-ion battery

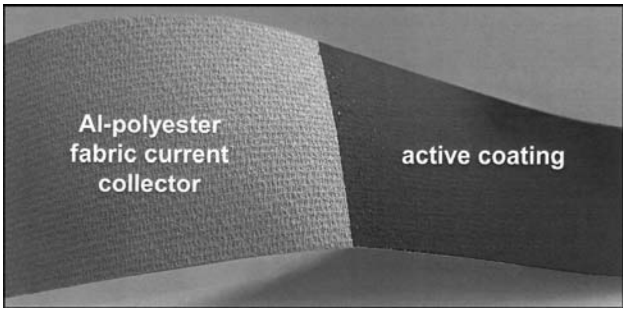

Fig. 13 Flexible lithium-ion cathode based on flame sprayed aluminum coatings onto polyester fabrics

materials, the elasticity and strength of the electrode rise, rendering feasible the production of flexible and soft batteries. Figure 13 shows a cathode designed for lithium-ion batteries. This cathode was produced using an aluminum flame sprayed fabric combined with an electrically active ceramic layer. Such produced batteries have already been successfully tested. In a near future, it is planned to upscale the process to produce aluminum-coated textile fabrics using a continuous flame spray process.

4. Conclusions

Electrically conductive powder and wire flame sprayed aluminum coatings were successfully deposited onto various polyester textile materials. Coatings produced using wire as raw material have a much better coating morphology than those produced using powder as starting material. By optimizing the spray parameters, electrical surface conductivity values of up to 500 S_A could be achieved. The fabric texture has a strong influence on the coating quantities necessary to obtain a good surface conductivity. Typical coating quantities lie around 20 mg/cm^2 for one-sided coated samples by using optimized spray parameter and an adequate cooling system.

However, by using a specific double-sided coated fabric, this quantity may be decreased to 15 mg/cm^2 or less and still produce coatings with good electrical surface conductivity values. To obtain these high conductivity values coupled with low coating quantities, an adequate cooling system for the substrate (air amplifiers) is essential. The shorter spray distances associated with such cooling systems enable a better particle melting, which in turn produces a more homogeneous coating structure, while retaining the flexibility of the fabric.

Successful preliminary test results for Al-polyester composites used as current collectors show that application-specific electrically conductive composites with adjustable specific surface conductivity values and microstructures can be produced on flexible fabric substrates without inducing any thermal or chemical damages to the fabric material.

It is intended in a near future to decrease the quantity of deposited aluminum while maintaining an adequate surface conductivity of the coatings for the application, which means finding a compromise between flexibility and conductivity.

Acknowledgments

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