HIGH-RATE MANUFACTURING OF THERMOPLASTIC COMPOSITES WITH ELECTRICALLY CONDUCTIVE CONSTITUENTS

Jessica Lavorata
Purdue University, Manufacturing Design Lab (MDLab)
Patrick Blanchard
Ford Motor Company, Research and Advanced Engineering
Jan-Anders E. Mansson
Purdue University, Manufacturing Design Lab (MDLab)

Abstract

As polymer composites gain popularity in the automotive industry, there is an increasing demand for advanced, lightweight materials with multifunctional capabilities that can be produced at a competitive cost and rate. This paper introduces a new manufacturing method and material system, referred to as M-TOW® (multifunctional-tow) which uses a novel overbraiding technique to compact thermoplastic prepreg tape into a cylindrical rod and maintain consolidation of this rod during subsequent processing steps. In these subsequent steps, the M-TOW® is reheated, formed into complex shapes, and overmolded to become localized structural reinforcement in injection molded parts. Historically, fiber-reinforced composite parts have succeeded at exceeding the mechanical properties of their metal counterparts but have not been usable in applications that require substantial electrical conductivity. This work offers solutions for integrating electrical conductivity into hybrid molded composite structures by overbraiding highly conductive wire onto the consolidated tow. The processability and conductivity performance of different wire geometries were compared before and after the forming stage. Results conclude that the integration of conductive wires into thermoplastic preforms is a viable means of extending the functionality of lightweight, high strength continuous fiber composites using high-rate manufacturing methods.

Introduction

The aerospace and automotive industries have continued to convert parts from metal to composites as composites offer high specific strength and stiffness. In the automotive industry, the emergence of electrical vehicles has led to metal components being replaced with injection-molded polymer composites as the reduced weight improves the range of the vehicle. The replacement of metal has exposed a need for electrically conductive pathways to be present within the vehicle for electromagnetic interference (EMI) shielding as well as for grounding parts to prevent the accumulation of static charge.

The aerospace industry has similar conductivity needs to the automotive industry, with the added consideration of lightning strike protection. During lightning strikes, high amounts of current is conducted onto the surface of the aircraft, requiring an electrically conductive pathway to create a path of least resistance for the current to safely exit the aircraft at a different point [1–3]. A common method of protecting aircraft from the large amounts of current produced is through introducing metallic layers into the laminated composites in the form of a foil or mesh [1, 3]. Metal foil is appealing because it is ultra-thin, but causes delamination and debonding when molded into composites [4]. Alternatively, metal meshes come in a variety of designs and thicknesses but require additional processing to adhere the mesh to the composite structure. Aluminum and copper are the most used metal materials due to their cost effectiveness and relatively high specific electrical conductivity. However, aluminum may experience galvanic corrosion in the presence of carbon which requires isolation layers to be introduced in the layup [5]. Copper, while being a slightly denser material than aluminum, does not require these additional layers, but requires a thicker mesh to be used to minimize the area damaged by the lightning strike [5, 6].

Current research being done to improve the conductivity of composites has focused on using conductive fillers or metallic layers within the composite. Conductive fillers, especially carbon-based (e.g. carbon nanotubes and graphene) or metallic (e.g. copper and aluminum) fillers, are compounded into the matrix to increase the composite's conductivity while maintaining a low weight [2, 7, 8]. Because the fillers can only be introduced in small quantities (< 15 weight % [7]) due to processability limitations, the overall conductivity of the part is significantly less (< 0.5 % of copper conductivity [7]) than the individual filler constituents. When the low-conductivity values are coupled with high material cost, conductive fillers are currently not feasible for industry to adopt.

A promising alternative to conductive fillers and laminated composites is hybrid composites. This approach introduces localized reinforcement or functionality by embedding a composite preform into an injection-molded part. Previous work [9–12] has demonstrated the utility and feasibility of this approach by embedding unidirectional thermoplastic tow into injection-molded parts for structural reinforcement. However, if the unidirectional tow can be made conductive, the preform can transport electricity through the resulting part. This paper examines one method of introducing functionality (electrical conductivity) to composite tow by incorporating metallic wires into the tow without compromising the weight, cost, or processability of the final part.

The scope of the present work is as follows. Building on the existing M-TOW® (multi-tow) line [13], a new approach to functionalization of the resulting tow by incorporating metallic material into the process's novel overbraiding stage is outlined. The resulting conductive tow was then subjected to forming, as well as electrical conductivity testing. In section 2, the methods of sample preparation and conductivity testing are outlined. In section 3, the results of the conductivity tests are discussed, as well as an analysis of the cost and weight savings of this functional tow. The goal of the paper is to show why M-TOW® holds promise as a method of achieving high electrical conductivity with a low weight and cost penalty through the incorporation of functional components.

Methods

M-TOW® manufacturing

The conductive composite examined was produced at a lab-scale at a rate of 0.8 m/min on the novel M-TOW® manufacturing line, produced and patented by EELCEE Ltd [13]. As shown in Figure 1, this line consists of eight integrated units that span a total length of 15 meters. The purpose of the line is to form continuous fiber reinforced thermoplastic prepreg into a compact and consolidated tow with a circular cross section, as seen in Figure 2 [14].

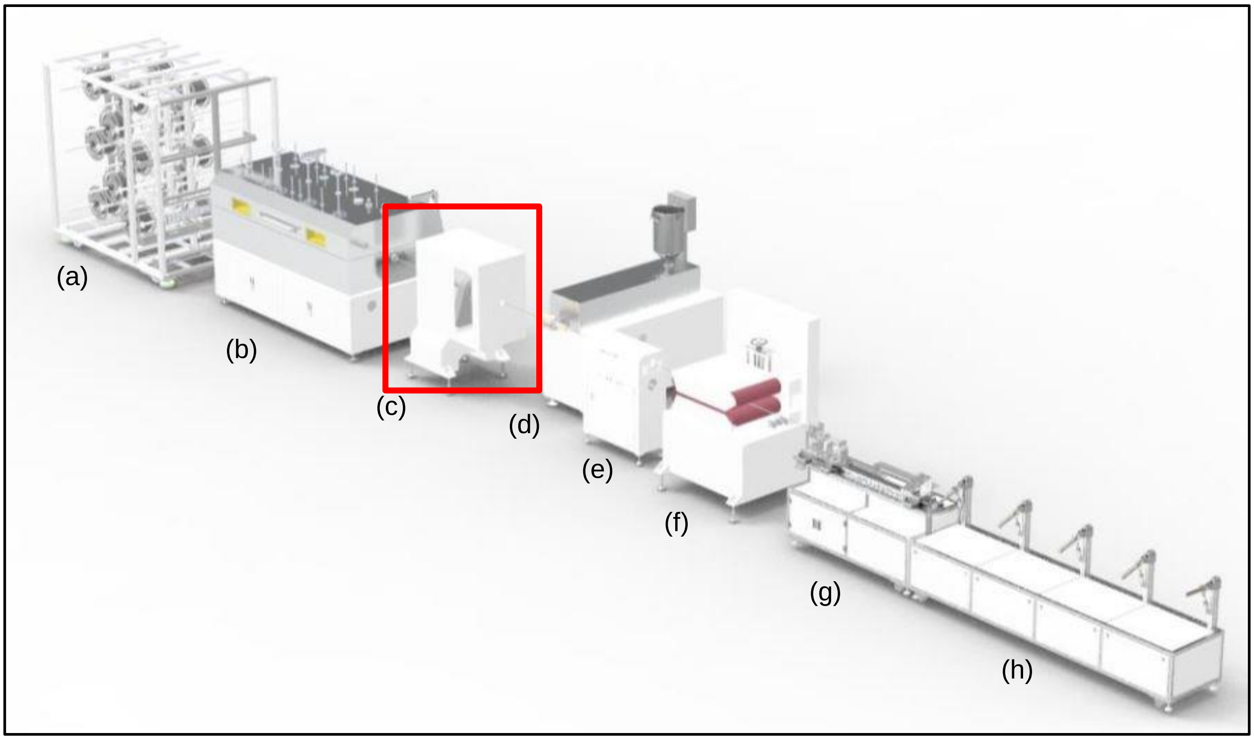

Figure 1: Overview of M-TOW® line. Components shown include a) creel, b) oven, c) braider, d) extruder, e) cooler, f) puller, g) cutter, h) stacker. Image courtesy of EELCEE Ltd [13].

The most unique aspect of the M-TOW® process is the overbraiding stage. Upon exiting the oven, the molten tow enters the braider (Figure 1c). Here, the tow itself acts as a mandrel while 8-16 yarns (or wires) interlace using a standard maypole braiding technique. As the tow is being continuously pulled through the manufacturing line, the tensioned yarns apply a radial force to the tow which locks the braided yarns in place by slightly embedding the yarns into the molten polymer. Additionally, these tensioned yarns control the tow's geometry by consolidating the thermoplastic melt into a cylindrical cross-section, shown in Figure 2. While this overbraiding process was initially designed to use glass fiber, this work examines the material produced when copper wire is used in the overbraid process, a process which holds a provisional patent [15].

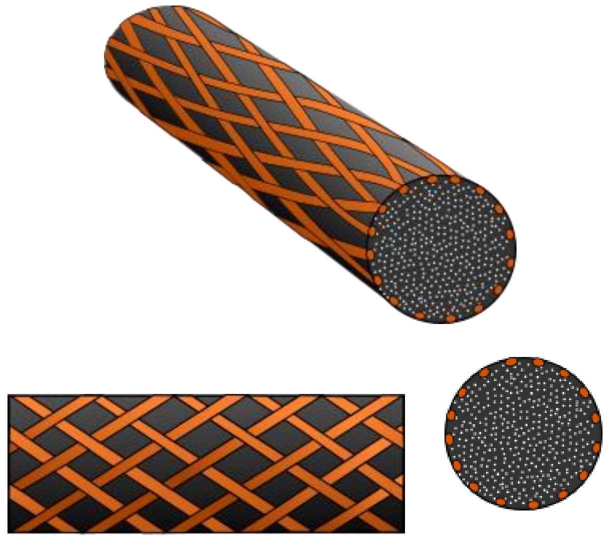

Figure 2: Representation of M-TOW® with 16 wires of copper overbraid. The glass fibers in the prepreg consolidate to the center of the tow while the wires embed into the surface polymer to create a circular rod/tow.

Materials

40 weight percent E-glass-reinforced polypropylene prepreg was provided by LOTTE Chemical Corp. and used for the M-TOW® core. The prepreg was slit into eleven tapes 11 mm wide x 0.60 mm thick. When consolidated and compacted, the final M-TOW® has a diameter of 9 mm. The biaxial overbraid for the non-conductive reference M-TOW® consisted of eight bobbins of dry 300 Tex E-glass fiber. For the conductive M-TOW® comparison, various sizes of electrolytic tough pitch (ETP) copper were used during overbraiding and compared during analysis. An overview of M-TOW® samples used is provided in Table I.

Table I. Overview of overbraided M-TOW® samples

Sample description	AWG† size used for overbraiding	Wire diameter (mm)	# overbraided wires used
GF x 8	--	--	8*
30 AWG x 8	30	0.254	8
30 AWG x 16			16
24 AWG x 8	24	0.510	8
24 AWG x 16			16
18 AWG x 8	18	1.024	8
18 AWG x 16			16

*GF x 8 was overbraided with dry E-glass fiber

†American wire gauge

In ideal processing conditions, the tow is slightly molten during the overbraiding stage which allows for the wire to partially embed into the tow, resulting in a consolidated and compact circular tow. An overview of the samples is shown in Figure 3. The 18 AWG wire was unable to embed into the tow due to the stiffness of such thick wire. In this case, the overbraid formed a “cage” around the tow. As a result of impractical processing conditions, samples 18 AWG x 8 and 18 AWG x 16 were not analyzed further.

Figure 3: M-TOW® samples with overbraided copper wire. From bottom to top: a) 30 AWG x 8, b) 30 AWG x 16, c) 24 AWG x 8, d) 24 AWG x 16, e) 18 AWG x 8, f) 18 AWG x 16.

Electrical conductivity testing

The electrical conductivity test setup is shown schematically in Figure 4. A DC power supply was used to provide constant 30 V (1.57 A) to the system. Resistors with a total of 19 Ω resistance rated at 25 W were placed in series with the M-TOW® sample. A voltmeter was used to measure the voltage drop across the sample which was used to calculate the sample resistance using Ohm’s law. Twenty measurements were taken on each sample for the purpose of statistical analysis of the results.

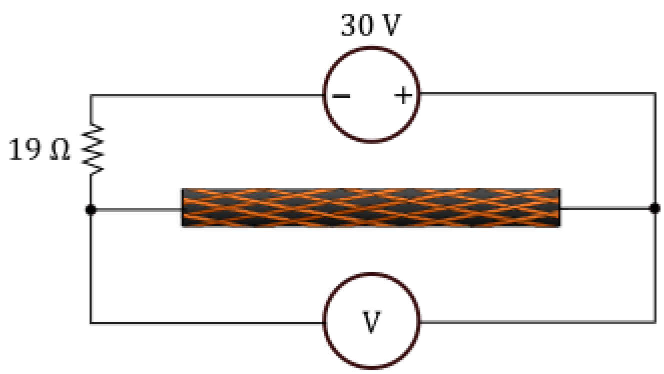

Figure 4. Schematic of test setup for the determination of the M-TOW® electrical conductivity. A constant 30 V DC power supply was used while a voltmeter measured the voltage drop across the sample.

Once the voltage drop across the sample was measured, the conductivity of the M-TOW® was calculated and compared to the theoretical conductivity of pure copper wire. For a measured voltage drop V at an applied current I, the conductivity σ can be determined:

$$\sigma = \frac{LI}{AV} \quad [1]$$

σ = conductivity, L = length, and A = cross-sectional area of wire. An overview of the parameters used during testing are provided in Table .

To ensure the persistence of the electrical conductivities in-situ, the original composite preform rods were formed and resubjected to electrical conductivity testing. The length of the samples varied for each test and the samples were tested both before and after forming, as shown in Figure 5. The formed specimens were heated and wrapped 1.5 times around an injection-molded polyamide 66 bushing at an exit angle of 40 degrees.

Table II. Testing parameters used for calculating sample conductivity

Sample description	**AWG**	**Wire diameter (mm)**	**# wires used**	**Total area (m^2)**	**Theoretical Resistance @ 20 °C (Ωm^{-1})**
30 AWG x 8	30	0.254	8	4.05×10^{-7}	0.3385
30 AWG x 16			16	8.11×10^{-7}	
24 AWG x 8	24	0.51	8	1.64×10^{-6}	0.0842
24 AWG x 16			16	3.28×10^{-6}	
18 AWG x 8	18	1.024	8	6.58×10^{-6}	0.0209
18 AWG x 16			16	1.32×10^{-5}	

(a) (b)

Figure 5. Samples tested for electrical conductivity (a) before and (b) after forming.

To verify the theoretical conductivities of pure copper, 3 m of single-strand wire for each gauge were tested with the same setup shown in Figure 4. The results of these tests demonstrated that the testing procedure can accurately measure electric conductivity.

Results

Electrical Conductivity

Figure 6 displays the results of the electrical conductivity tests for the samples before and after forming. For all tests, the formed samples displayed higher conductivity than the straight samples. This phenomenon is due to increased contact between the wires when wrapped around the bushings which decreases the overall resistance of the sample, thus increasing conductivity. As the wire size and number of wires used increases, the electrical conductivity also increases. An outlier to this trend is for 30 AWG x 8 which has significantly higher conductivity than expected. Since the braid density is lowest for this sample, the tow is less constrained during forming which allows it to flatten against the bushing. This allows the wires to have increased contact, thus increasing the electrical conductivity. Future studies would adjust the temperature and force applied during forming to produce the same cross section for all samples, regardless of the braid density.

The electrical conductivity results were normalized to the measured baseline values of a single copper wire of the corresponding wire gauge to observe the effect on conductivity due to incorporation into the tow. The “base” electrical conductivity is shown for comparison in Figure 6 and has values of $5.53 \times 10^7\ \mathrm{S/m}$ and $5.63 \times 10^7\ \mathrm{S/m}$ for 30 AWG and 24 AWG, respectively. The conductivity of the tested samples ranges from 83.6% – 94% of the base values, demonstrating that the overbraiding and forming processes slightly decrease the effective conductivity of the copper wire. Little statistical error was observed in the measurements, as shown in Figure 6. The result that the calculated conductivities fall below the baseline value is to be expected as these conductivities neglect the effect that the braid has on the copper. The true wire length will differ from the tow length due to the helical path of the braid along the tow. The resulting effective conductivity of the tow should be lower than the baseline copper value, as is seen in Figure 6.

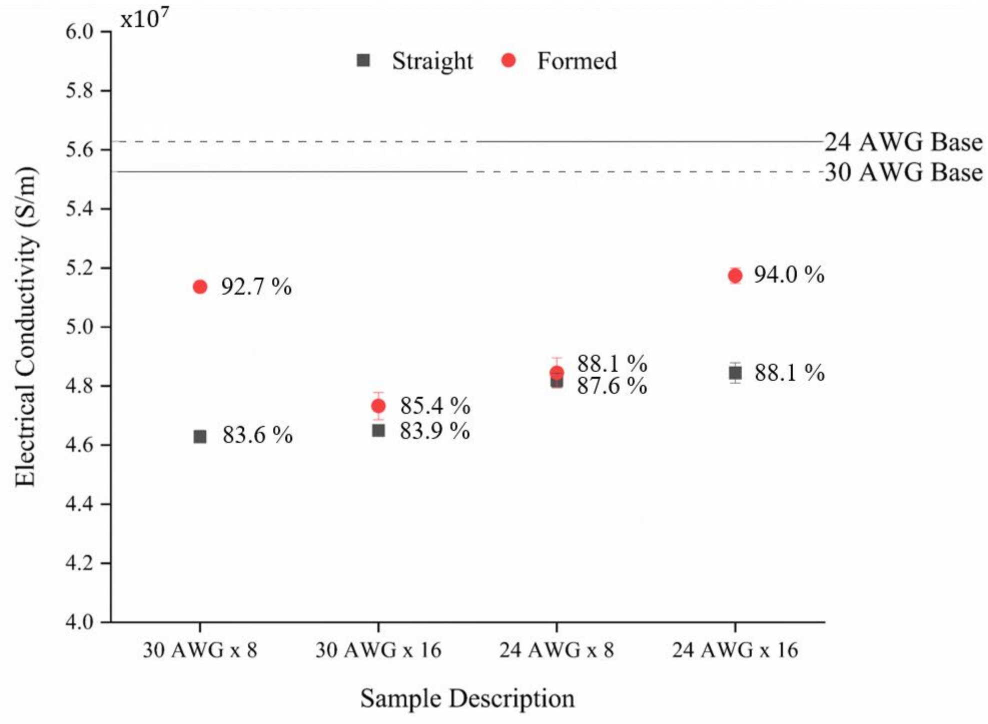

Figure 6. Electrical conductivity of functional M-TOW® compared before (straight) and after (formed) forming. Fractional conductivities with respect to the baseline value are labelled. Error bars represent one standard error of the measurement set.

Cost and Weight Savings

Unlike alternative methods used to produce conductive composites where the conductive constituent is distributed throughout the entire part, M-TOW® is implemented in hybrid manufacturing where the M-TOW® is placed only where the structure needs support or a conductive pathway. In a large part, the M-TOW® could account for less than 5 % of the total structural weight, but improve structural performance by over 200 % [10].

The calculated cost and weight of the overbraided M-TOW® samples is provided in Table . The base GF x 8 sample was produced with 40 weight percent glass fiber and 60 weight percent polypropylene. The cost of glass fiber and polypropylene used in the calculations was $2.00/kg and $1.10/kg, respectively. Regardless of copper size and number of wires used in the overbraid, the effect of the overbraid on the total weight of the M-TOW® is minimal. The effect of wire size influences the final cost of the M-TOW®, but when compared to other conductive composites (e.g. carbon nanotube fillers), the conductive M-TOW® remains a low cost and advantageous method to introduce conductivity to composite structures.

Table III. Cost comparison for overbraided M-TOW®

Sample description	Volume of copper in M-TOW® (%)	Total weight of M-TOW® (kg/m)	Copper cost ($/kg)	M-TOW® cost ($/kg)	M-TOW® cost ($/m)
GF x 8	0.0	0.103	2.00*	6.00	0.62
30 AWG x 8	0.7	0.106	42.06	7.44	0.79
30 AWG x 16	1.4	0.110	42.06	8.74	0.96
24 AWG x 8	2.91	0.119	31.59	9.73	1.16
24 AWG x 16	5.65	0.136	31.59	12.49	1.70
*GF x 8 reflects the cost of dry E-glass fiber					

Conclusions

This work introduced a promising approach to achieving electrical conductivity in polymer composites by introducing metallic material to the process's novel overbraiding stage. The electrical conductivity was measured before and after forming and a trend was seen where improved electrical conductivity occurs after forming, reaching 94 % of the theoretical value of copper. The total length of the helical path that the copper travels during overbraiding will be included in future calculations to obtain values closer to the theoretical calculations. Future work will also include the thermal conductivity performance of the M-TOW®.

More generally, this work demonstrated that hybrid manufacturing can introduce localized, targeted functionality. If the unidirectional tow is made conductive, the preform can transport electricity through the resulting part. Overall, the copper overbraided samples did not introduce a high cost or weight penalty, and when coupled with hybrid manufacturing, offer a promising solution to introducing conductive pathways to composite structures.

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Declaration of Conflicting Interest

Dr. Jan-Anders Mansson is the founder and shareholder of EELCEE Ltd., the manufacturer of the M-TOW® line used in this research and the company may potentially benefit from the research results. Dr. Mansson's relationship with EELCEE Ltd. has been reviewed and managed by Purdue University in accordance with its conflict of interest policies.

Full legal disclaimer

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