METHOD OF FORMING A COMPOSITE PART WITH COMPLEX CARBON FIBER ARCHITECTURE BY RESISTIVE HEATING

Abstract: The present invention provides a method for forming a composite part. The method includes providing a forming surface (160), which can be either generally flat or curved depending upon the shape of the composite to be formed. Providing a pre-form part with a part structure adapted to engage the forming surface. The part structure is defined by the arrangement of a plurality of electrically conductive carbon fibers. Placing the pre-form part on the forming surface. Injecting or infusing resin (118), either thermoset or thermoplastic, into the pre-form part via an injection port. Applying an electric current to the carbon fibers to resistively heat the carbon fibers and the pre-form part. As the pre-form part is heated, the resin permeates the part and current is further applied until the part sets. According to another aspect of the invention, the carbon fibers are combined with non-electrically conductive fibers to form either a flat or curved part structure. Additionally, the non-conductive fibers may be thermoplastic fibers that will form the resin matrix of the part and possibly eliminate any further injection of resin.
METHOD OF FORMING A COMPOSITE PART WITH
COMPLEX CARBON FIBER ARCHITECTURE
BY RESISTIVE HEATING

Technical Field

This invention relates generally to a method of forming a composite part from a pre-form part. More particularly, the present invention relates to a method of forming a composite part by applying electric current to resistively heat and cure a pre-form part with resin, where the pre-form has a complex carbon fiber architecture.

Related Cases

The present invention claims priority from provisional application no. 60/197,136.

Background of the Invention

The technology and methods for producing composite material parts are quite diverse. At one end of the spectrum, there exists low cost, low quality composite parts. At the other end of the spectrum, are high quality, advanced composite parts. Although advanced composite parts are costly to produce, both types of composite parts are desirable for use in many applications because of their high strength, low weight, and increased dimensional stability. In the past, composite parts were used in military and defense-related applications and more recently, composite parts have been used in civilian applications, including bridges, automobiles, and sporting goods. However, composite parts have been precluded from entering a number of applications for which they are better suited than the materials currently used.

Traditionally, composite parts have been formed with the use of an oven or press to heat and cure a pre-form part held in a mold and injected with resin.
These conventional methods suffer from a number of inherent limitations. First, the application of heat used to cure the pre-form part and the resin is inexact and not confined to a precise location because heat is applied across the entire mold. Second, the ovens, presses, and molds are complicated and expensive to fabricate. Third, the molds are generally large in size, which increases the oven’s power consumption and cycle times as the warm-up and cool-down times are lengthened. Fourth, because heat is applied from an outside surface of the pre-form part, curing efficiency is reduced with conventional ovens or presses. Specifically, the inner portions of thick pre-form parts experience incomplete cure, and for parts with irregular dimensions, thinner portions cure before thicker portions. Lastly, conventional methods are inefficient for post-curing of composite parts, which is necessary when the composite part is used in a harsh or corrosive environment.

A variety of pre-form parts have been used with the conventional methods to form composite parts. For example, carbon fibers have been employed in the pre-form part; however, the problems associated with the conventional methods remain for pre-form parts with carbon fibers. Therefore, there is a genuine need for a low cost, efficient method to produce composite parts formed from a carbon fiber pre-form part.

**Summary of the Invention**

The present invention provides a method of forming a composite part from a pre-form part with complex carbon fiber architecture by resistively heating the pre-form part.

According to one aspect of the invention, the method comprises the steps of providing a forming surface; providing a pre-form part having a part structure adapted to engage the forming surface, the part structure defined by an arrangement of electrically conductive carbon fibers; placing the pre-form part on the forming surface; introducing resin with an initially high viscosity into the pre-form part; applying an electric current to the carbon fibers to resistively heat the carbon fibers, thereby heating the pre-form part such that the resin viscosity is
lowered and the resin permeates the part; and, further applying electric current such that the part sets.

Although the part structure is adapted to engage the forming surface, the structure of the pre-form part is dependent upon how the carbon fibers are arranged or bundled throughout the part. For example, the carbon fibers can be braided to form a generally flat part structure or a curved part structure. Also, the carbon fibers can be knitted to form a form a generally flat part structure or a curved part structure. Lastly, the carbon fibers can be stitch bonded to form a generally flat part structure or a curved part structure.

According to another aspect of the invention, the pre-form part is formed from a combination of electrically conductive carbon fibers and non-electrically conductive fibers. In this aspect, the method comprises the steps of providing a forming surface; providing a pre-form part having a part structure adapted to engage the forming surface, the part structure defined by a combination of carbon fibers and non-electrically conductive fibers; placing the pre-form part on the forming surface; introducing a resin into the pre-form part; applying an electric current to the carbon fibers to resistively heat the carbon fibers, thereby heating the pre-form part such that the resin permeates the part and the part sets or cures.

The structure of the pre-form part is dependent upon how the carbon fibers and the non-electrically conductive fibers are combined. For example, the carbon fibers and the non-electrically conductive fibers can be braided to form a generally flat part structure or a curved part structure. Alternatively, the carbon fibers and the non-electrically conductive fibers can be knitted to form a form a generally flat part structure or a curved part structure. Finally, the carbon fibers and the non-electrically conductive fibers can be stitch bonded to form a generally flat part structure or a curved part structure.

As compared to conventional molding methods, resistive heating of the pre-form part has a number of significant advantages. First, resistive heating is considerably more energy efficient as electric current is precisely applied to heat an exact location of the part. In contrast, conventional methods apply heat across
the mold and the press or oven, thus heat is not confined to an exact location. Second, unlike conventional methods, resistive heating requires only a AC/DC power source and leads to the pre-form part. Third, the cure cycle time for resistive heating is considerably less because there is no oven or press and the pre-form part has less mass to heat. To the contrary, conventional presses and ovens have greater masses, which increases the warm-up and cool-down times, thereby increasing the cycle times. Finally, resistive heating ensures a more uniform cure for thick and irregularly shaped pre-form parts by reducing temperature lags throughout the pre-from part. In contrast, conventional methods cannot ensure uniform curing for thick parts because the surface of the part cures before the interior of the part. In addition, conventional methods cannot ensure uniform curing for irregularly shaped parts because thinner sections cure before thicker sections.

In a further embodiment, all or some of the non-electrically conductive fibers in the preform part can be thermoplastic fibers such as polypropylene, nylon or any suitable combination of engineered thermoplastic fibers. These fibers can be oriented to be in intimate contact with the heat generating, electrically conductive fibers. This can be accomplished by twisting, commingling, or locating these fibers in close proximity to the electrically conductive fibers. As heat is produced by the electrically conductive fibers, the thermoplastic fibers are caused to melt and flow into the electrically conductive fibers and other non-electrically conductive fibers (if present) that are not thermoplastic in nature. As the part cools, the thermoplastic resin hardens forming a structural composite.

Further aspects of the invention are disclosed in the detailed description of the preferred embodiment, the drawings and the claims.
Detailed Description of the Figures

Figure 1 is a perspective view of a pre-preg or pre-form part and a forming surface according to the invention;

Figure 2 is a partial cross-section of the pre-form part of Fig. 1, along line I-I;

Figure 3 is an end view of a pre-form part, a curved forming structure, a resin injection port with resin, and power leads connected to carbon fibers in the pre-form part in accordance with an aspect of the present invention;

Figure 4 is a perspective view of a pre-preg part and a forming surface in accordance with an aspect of the present invention;

Figure 5 is a partial cross-section of the pre-form part of Fig. 4, along line II-II, showing carbon fibers and non-electrically conductive fibers;

Figure 6 is an end view of a pre-form part, a curved forming structure, a resin injection port with resin, and power leads connected to carbon fibers in the pre-form part in accordance with an aspect of the present invention;

Figure 7 is a representation of a fiber braid weave in accordance with an aspect of the present invention;

Figure 8 is an end view of curved fiber braids in accordance with an aspect of the present invention;

Figure 9 is an example of a finished curved composite part formed from either braided or knitted fibers in accordance with an aspect of the present invention;

Figure 10 is an example of a finished curved composite part formed from knitted fibers in accordance with an aspect of the present invention;

Figure 11 is an example of a finished curved composite part formed from stitch bonded fibers in accordance with an aspect of the present invention;

Figure 12 is an example of a finished curved composite part formed from stitch bonded fibers in accordance with an aspect of the present invention;

Figure 13 is perspective view of an open mold and pre-form part in accordance with an aspect of the present invention;
Figure 14 is perspective view of the pre-form of Figure 13 placed in the open mold and connected to a resin reservoir and an electrical power supply;

Figure 15 is a perspective view of the pre-form, mold, power supply and reservoir of Figure 16, with a vacuum pump;

Figure 16 is a perspective view of the pre-form, mold, power supply, reservoir and pump of Figure 17 with resin partially injected into the pre-form part;

Figure 17 is a cross-sectional view of the pre-form part of Figure 13 along the line III-III, showing bundles of electrically conductive fibers between layers of non-electrically conductive fibers;

Figure 18 is cross-section of an alternative embodiment of the pre-form of Figure 13 having thermoplastic fibers co-mingled with the electrically conductive fibers within the bundles of fibers; and,

Figure 19 is cross-section of a further alternative embodiment of the pre-form of Figure 13 having thermoplastic fiber bundles co-mingled with the electrically conductive fiber bundles.

**Detailed Description of the Preferred Embodiment**

While the invention is susceptible of embodiment in many different forms, there is shown in the drawings and will herein be described in detail a preferred embodiment of the invention. It is to be understood that the present disclosure is to be considered as an exemplification of the principles of the invention. This disclosure is not intended to limit the broad aspects of the invention to the illustrated embodiments.

The present invention provides a method of forming a composite part. As shown in Fig.1, a forming surface 10 is provided. A pre-form part 12 is then provided with a part structure 14. The pre-form part 12 is adapted to engage the forming surface 10. Referring to Fig. 2, the part structure 14 is defined by a plurality of carbon fibers 16. As shown in Fig. 3, the pre-form part 12 is then placed on the forming structure 10 and resin 18, having a relatively high viscosity,
is introduced into the pre-form part 12 via a resin injection port 19. Leads 20 are then connected to a portion of the carbon fibers 16 such that electric current is applied to the carbon fibers 16 to resistively heat the carbon fibers 16 and the pre-form part 12. While the current is applied, the temperature of the pre-form part 12 increases thereby lowering the viscosity of the resin 18 such that resin 18 flows and permeates the pre-form part 12. Electric current continues to be applied to the carbon fibers 16 until the pre-form part 12 sets to form the finished composite part 22.

The part structure 14 is designed to match the shape and configuration of the forming surface 10. For example, if the forming surface 10 is flat, then the carbon fibers 16 are commingled to form a flat part structure 14. The carbon fibers 16 can be braided, knitted, or stitch-bonded to form the flat part structure 14. If the forming surface 10 is a curved, non-linear shape (i.e., a light post or a tennis racket), then the carbon fibers 16 are commingled or arranged to form a curved part structure 14. In either the light post or tennis racket examples, the forming surface 10 acts like a mandrel, about which the pre-form part 12 is placed. To form the curved part structure 14, the carbon fibers 16 can be braided, knitted, or stitch-bonded. Because the majority of commercial applications involve complex, curved shapes, such as pyramids, spheres and cylinders, the ability of the carbon fibers 16 to form curved part structures is commercially valuable.

In another preferred embodiment, the method of forming a composite part comprises the following steps. As shown in Fig. 4, a forming surface 24 is provided. A pre-form part 26 is then provided with a part structure 28. The pre-form part 26 is adapted to engage the forming surface 24. Referring to Fig. 5, the part structure 28 is defined by a combination of carbon fibers 30 and non-electrically conductive fibers 32. As shown in Fig. 6, the pre-form part 26 is then placed on the forming structure 24 and resin 34, having a relatively high viscosity, is introduced into the pre-form part 26 via a resin injection port 35. Leads 36 are then connected to a portion of the carbon fibers 32 such that electric current is applied to the carbon fibers 30 to resistively heat both the carbon fibers 30 and the
pre-form part 26. When electric current is applied, the temperature of the pre-form part 26 increases thereby reducing the viscosity of the resin 34 such that the resin 34 flows and permeates the pre-form part 26. Electric current continues to be applied to the carbon fibers 30 until the pre-form part 26 sets to form the finished composite part 38. In this embodiment, the resultant composite part 38 includes the carbon fibers 30, the non-electrically conductive fibers 32, and the set resin 34.

The part structure 28 is designed to match the shape and configuration of the forming surface 24. Therefore, if the forming surface 24 is flat, then the carbon fibers 30 and the non-electrically conductive fibers 32 are combined to form a flat part structure 28. The carbon fibers 30 and the non-electrically conductive fibers 32 can be braided, knitted, or stitch-bonded to form the flat part structure 28. If the forming surface 24 is a curved, non-linear shape, then the carbon fibers 30 and the non-electrically conductive fibers 32 are combined to form a curved part structure 28. To form the curved part structure 28, the carbon fibers 30 and the non-electrically conductive fibers 32 are braided, knitted, or stitch-bonded.

The resin could be either thermoset or thermoplastic resin. When thermoset resin is used in the method, the pre-form parts 12, 26 "cures" and the resin undergoes a permanent phase change. In contrast, when thermoplastic resin is used in the method, the pre-form part 12, 26 "forms" and the resin does not experience a phase change. Thus, unlike a cured thermoset resin part, the formed thermoplastic resin composite part 38 can be re-formed into another desired shape.

The use of non-electrically conductive fibers 32 reduces the cost of the finished composite part 38 while maintaining the necessary physical properties of the composite part 38, such as strength and weight. The various types of non-electrically conductive fibers 32 include, but are not limited to glass, aramid, quartz, and ceramic fibers. Each variety of non-electrically conductive fibers 32 has distinct performance attributes, including strength, weight, abrasion resistance, flexibility, surface impact resistance, heat resistance, and heat resistance behavior that can be advantageously selected depending on the performance criteria established for the finished product. Consequently, the performance characteristics
of the composite part 38 depend in part from the type of non-electrically conductive fibers 32 combined with the carbon fibers 30.

The resin could be either injected or infused into the pre-formed part. Injection is appropriate when there are two forming surfaces but a high pressure is required to ensure proper resin injection. Infusion is appropriate when there is only one forming surface but a membrane is required to facilitate the drawing of a vacuum.

In another preferred embodiment, the pre-form part and the part structure result from carbon fibers that are formed into a non-woven mat, such as a Conoco product made from mesophase fibers or a Fortafil product manufactured using pan based fibers. In the non-woven mat, the carbon fibers can be randomly arranged such that the mat is very pliable. A non-woven carbon fiber mat is extremely beneficial for forming curved composite parts because it is flexible and easily conformed to a curved forming surface. Typically, non-woven carbon fiber mats have a lower material cost thereby reducing the composite part cost. To increase the strength of the composite part but reduce material costs, the non-woven mat can also include an arrangement of non-electrically conductive fibers with the carbon fibers. The non-electrically conductive fibers include, but are not limited to glass, aramid, quartz, and ceramic fibers.

In another preferred embodiment, electric current is applied to the carbon fibers to resistively heat the carbon fibers and the pre-form part before the resin is introduced. Once the pre-form part has been suitably heated, then resin is introduced via an injection port. This pre-heating of the pre-form part facilitates a more efficient resin injection by lowering the resin viscosity. This also lowers the injection pressures required and allows the use of less expensive, low pressure molds. The amount of electric current is increased until the resin permeates the part and the part sets, meaning cures for thermoset resins and forms for thermoplastic resins.

Examples of parts that can be formed using this process are shown in Figures 8-12.
An open mold 100 having a plurality of vacuum ports 102 and a resin injection port 104 is shown in Figure 13. The open mold further includes a complex shaped forming surface 108 and a flexible membrane 110. A pre-form part 120 having a portion 140 shaped to coincide with the forming surface 108 is shown outside of the mold 100 disclosed in Figure 13.

As shown in Figure 14, the pre-form part 120 is placed in the mold 100 with the shaped surface 140 positioned on the forming surface 108. The mold 100 is connected to an electrical power source 112 by lines 114. Additionally, the mold 100 is connected to a reservoir 116 of resin 118 by a conduit 119. Referring to Figure 15, the mold 100 is also connected to a vacuum pump 122 by a hose 124.

In operation, the electrical power source 112 is used to resistively heat electrically conductive fibers 126 (e.g., shown in cross-section in Figures 17 - 19), such as carbon fibers, in the pre-form part 120. This pre-heating step assists in lowering the viscosity of the resin 118 and facilitates infusion of the resin 118 into the pre-form part 120 as shown in Figure 16. The vacuum pump 122 is also used to assist in drawing the resin 118 into the pre-form part 120 and in keeping the pre-form part 120 in place in the mold 100.

The pre-form part 120 may be formed to include a plurality of bundles 128 of electrically conductive carbon fibers 126 contained within layers of 130 and 132 of non-electrically conductive fibers as shown in Figure 17. The bundles of fibers 128 may be braided, knitted or stitch bonded to form a flat shape or a more complex shape. In addition to the electrically conductive fibers 126, the bundles may include non-electrically conductive fibers to enhance the properties of the part and/or to provide savings in cost.

The non-conductive fibers in the bundles can be thermoplastic fibers 134. In one alternative, the electrically conductive fibers 126 can be co-mingled with thermoplastic fibers 134 within each bundle 128 as shown in Figure 18. In an alternative embodiment, the thermoplastic fibers 134 can be in separate bundles 134 co-mingled with the bundles 128 containing only electrically conductive fibers 126. In these embodiments, the thermoplastic fibers 134 act as the resin matrix.
such systems, it may not be necessary to inject additional resin into the pre-form part 120, thus eliminating the injection step from the process.

While specific embodiments have been illustrated and described, numerous modifications are possible without departing from the spirit of the invention, and the scope of protection is only limited by the scope of the accompanying claims.
We claim:

1. A method of forming a composite part, comprising the steps of:
   providing a forming surface;
   providing a pre-form part having a part structure adapted to engage the forming surface, the part structure defined by a plurality of carbon fibers;
   placing the pre-form part on the forming surface;
   introducing a resin into the pre-form part, the resin having an initially high viscosity;
   applying an electric current to the carbon fibers to resistively heat the carbon fibers, thereby heating the pre-from part such that the viscosity of the resin is reduced and the resin permeates the part; and,
   further applying an electric current such that the part sets.

2. The method of claim 1, further comprising braiding said carbon fibers such that the part structure is generally flat.

3. The method of claim 2, wherein the resin is a thermoset resin.

4. The method of claim 2, wherein the resin is a thermoplastic resin.

5. The method of claim 1, further comprising braiding said carbon fibers such that the part structure is curved.

6. The method of claim 1, further comprising knitting said carbon fibers such that the part structure is generally flat.

7. The method of claim 1, further comprising knitting said carbon fibers such that the part structure is curved.

8. The method of claim 1, further comprising stitch bonding said carbon fibers such that the part structure is generally flat.

9. The method of claim 1, further comprising stitch bonding said carbon fibers such that the part structure is curved.
10. The method of claim 1, further comprising randomly arranging said carbon fibers into non-woven mat such that the part structure is generally flat.

11. The method of claim 1, further comprising randomly arranging said carbon fibers into non-woven mat such that the part structure is curved.

12. A method of forming a composite part, comprising the steps of:
   providing a forming surface;
   providing a pre-form part having a part structure adapted to engage the forming surface, the part structure defined by a combination of carbon fibers and non-electrically conductive fibers;
   placing the pre-form part on the forming surface;
   introducing a resin into the pre-form part, the resin having an initially high viscosity;
   applying an electric current to the carbon fibers to resistively heat the carbon fibers, thereby heating the pre-from part such that the viscosity of the resin is reduced and the resin permeates the part; and,
   further applying an electric current such that the part sets.

13. The method of claim 12, further comprising braiding said carbon fibers and the non-electrically conductive fibers such that the part structure is generally flat.

14. The method of claim 13, wherein the non-electrically conductive fibers are polyester fibers.

15. The method of claim 13, wherein the non-electrically conductive fibers are glass fibers.

16. The method of claim 13, wherein the non-electrically conductive fibers are aramid fibers.

17. The method of claim 13, wherein the non-electrically conductive fibers are quartz fibers.
18. The method of claim 13, wherein the non-electrically conductive fibers are ceramic fibers.

19. The method of claim 12, further comprising braiding said carbon fibers and the non-heat conductive fibers such that the part structure is generally flat, curved.

20. The method of claim 12, further comprising knitting said carbon fibers and the non-electrically conductive fibers such that the part structure is generally flat.

21. The method of claim 12, further comprising knitting said carbon fibers and the non-electrically conductive fibers such that the part structure is curved.

22. The method of claim 12, further comprising stitch bonding said carbon fibers and the non-electrically conductive fibers such that the part structure is generally flat.

23. The method of claim 12, further comprising stitch bonding said carbon fibers and the non-electrically conductive fibers such that the part structure is curved.

24. The method of claim 12, wherein the carbon fibers and the non-electrically conductive fibers are combined to form a non-woven mat such that part structure is generally flat.

25. The method of claim 12, wherein the carbon fibers and the non-electrically conductive fibers are combined to form a non-woven mat such that part structure is curved.

26. A method of forming a composite part, comprising the steps of:

   providing a forming surface;

   providing a pre-form part having a part structure adapted to engage the forming surface, the part structure defined by a combination of carbon fibers and non-electrically conductive fibers;

   placing the pre-form part on the forming surface;
applying an electric current to the carbon fibers to resistively heat the carbon fibers, thereby heating the part;

introducing a resin into the pre-form part, the resin having an initially high viscosity;

increasing the electric current to the carbon fibers to resistively heat the carbon fibers, thereby reducing the viscosity of the resin such that the resin permeates the part; and,

further applying an electric current such that the part sets.

27. A pre-form part comprising a plurality of electrically conductive fibers co-mingled with a plurality of thermoplastic fibers defining the part structure.

28. The pre-form part of claim 27 wherein said part comprises said electrically conductive fibers and said thermoplastic fibers formed into bundles having both said electrically conductive fibers and said thermoplastic fibers in said bundles.

29. The pre-form part of claim 27 wherein said electrically conductive fibers are formed into a first set of bundles and said thermoplastic fibers are formed into a second set of bundles co-mingled with said first set of bundles.

30. The pre-form part of claim 28 wherein said bundles of said electrically conductive fibers and said thermoplastic fibers are braided.

31. The pre-form part of claim 27 wherein said electrically conductive fibers are carbon fibers.

32. A method of forming a composite part comprising the steps of providing a pre-form part including a plurality of electrically conductive fibers in proximity with a plurality of thermoplastic fibers; and, applying an electric current to said carbon fibers to resistively heat said carbon fibers to melt said thermoplastic fibers.

33. The method of claim 32 further comprising co-mingling said carbon fibers and said thermoplastic fibers.
34. The method of claim 32 further comprising forming said carbon fibers and said thermoplastic fibers into bundles.

35. The method of claim 34 further comprising braiding said bundles.

36. The method of claim 34 further comprising knitting said bundles.

37. The method of claim 32 wherein said electrically conductive fibers are carbon fibers.