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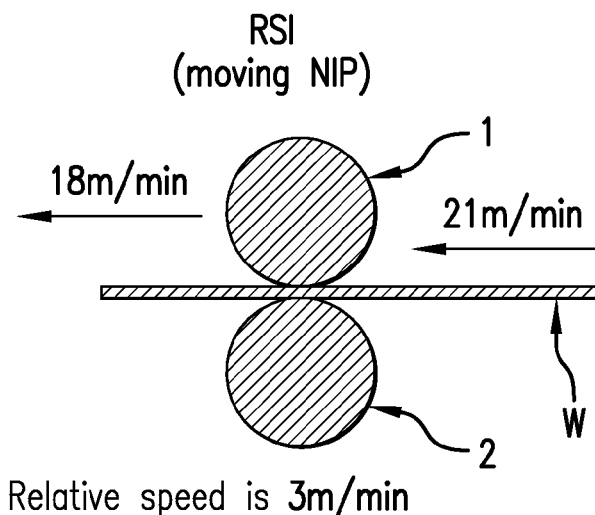


FIG.1

(57) Abstract: A method for impregnating a fibrous material with a curable resin to form a prepreg (22) is disclosed. The method includes conveying a web material through at least one moving pressure nip formed between a moving pressure roller (54) and a moving supporting surface, wherein the moving pressure roller (54) and the moving supporting surface travel at different velocities relative to each other resulting in a relative velocity (v_{rel}) between the web material and the pressure nip. The at least one moving pressure nip travels in the same direction as the web material while applying sufficient pressure to compress the web material and to affect impregnation of the fibrous material with the curable resin. Also disclosed is a system for implementing the disclosed impregnation method.

METHOD AND SYSTEM FOR IMPREGNATING FIBERS TO FORM A PREPREG

BACKGROUND

Prepreg composite materials have been widely used in various high-performance structures, such as aircraft and automobile components, and sport equipment (e.g., fishing rods, golf club shafts, badminton rackets, tennis rackets, etc.). A prepreg is a fiber reinforcement that is pre-impregnated with a matrix resin, typically a thermoset resin. The fibers reinforce the matrix resin, bearing the majority of the load supported by the prepreg material, while the resin matrix bears a minority portion of the load supported by the prepreg material and also transfers load from broken fibers to intact fibers. In this manner, the prepreg material can support greater loads than either the matrix resin or fibers can support alone. Furthermore, by tailoring the reinforcing fibers in a particular geometry or orientation, a composite material can be efficiently designed to minimize weight and volume while maximizing strength.

Prepregs may be manufactured by impregnating a web of continuous fibers or a fabric with a matrix resin, creating a pliable and tacky sheet of material. During impregnation, the reinforcing fibers are impregnated with the matrix resin in a controlled fashion. The precise specification of the fibers, their orientation and the formulation of the resin matrix can be specified to achieve the optimum performance for the intended use of the prepregs. The mass of fibers per square meter can also be specified according to requirements.

The term “impregnate” refers to the introduction of a matrix resin to reinforcement fibers so as to partially or fully encapsulate the fibers with the resin. The impregnation process controls the amount of resin inside the fiber bed and at the surface of the fiber bed. Furthermore, the resin impregnation level impacts the methods used to assemble the finished composite part and the part's quality. The matrix resin for making prepregs may

take the form of resin films or liquids. Typically, impregnation is facilitated by the application heat and/or pressure. The resulting prepregs produced from the prepreg fabrication process is in an uncured or curable state (i.e., not hardened) and may be frozen in order to inhibit the polymerization of the resin. For manufacturing composite parts from prepregs, the cold prepregs are thawed to room temperature, cut to size, and assembled on a molding tool through various methods, such as hand layup, Automated Tape Layup (ATL), and Advanced Fiber Placement (AFP). The prepreg material for each assembly method requires different levels of impregnation and different levels of tack. Level of "tack" refers to how well prepregs stick to one another and to a tool surface. For example, for hand layup, there is less need for high level of impregnation and greater need for tack while with AFP the fiber bed requires much higher levels of impregnation. Once in place, the prepregs are consolidated and cured under pressure to achieve the required fiber volume fraction with minimal voids.

Currently, many conventional methods for impregnating continuous fiber material involve the use of static pressure-applying mechanism. Roller nips, for example, have been used to supply pressure from a fixed position in space while a continuous web moves through the static nips. These conventional processes are generally limited to a web speed of 1 to 4 m/min for high impregnation of thick resin films and fiber materials. They are also limited in their operating temperatures as higher temperatures tend to cause problems with premature curing of the resin or swelling in the case of thermoplastic resin. Essentially, what dominates the prepreg world are the fundamental physical limitations outlined in Darcy's law: the rate of fluid flow is a function of the pressure supplied, the thickness of the body, the permeability of the body of interest and the viscosity of the fluid. In the case of carbon fiber webs, the body has a dynamic permeability and the fluid has a dynamic viscosity, i.e. viscosity which changes with shear rate and temperature. This law cannot be over-ridden. Different fiber materials, different resins, different pressures and web speeds all change the shape and movement of the function but do not change the law. So a static nip or a belt under certain pressures and temperatures will always limit the production speed of the

material. If the web is moving too fast, a static nip cannot press enough resin into the fiber web. If the temperature applied to the resin is too hot, the material will distort and will be ruined, and if too cold, there is insufficient force to
5 press the resin into the fiber web.

In light of the issues discussed above, there remains a need for an improved resin impregnation technique that can increase prepreg production rate without sacrificing the
10 control of impregnation level.

A reference herein to a patent document or any other matter identified as prior art, is not to be taken as an admission that the document or other matter was known or that
15 the information it contains was part of the common general knowledge as at the priority date of any of the claims.

Where any or all of the terms "comprise", "comprises", "comprised" or "comprising" are used in this specification
20 (including the claims) they are to be interpreted as specifying the presence of the stated features, integers, steps or components, but not precluding the presence of one or more other features, integers, steps or components.

25 SUMMARY OF THE INVENTION

A first aspect of the present invention provides a method of impregnating a fibrous material with a curable resin to form a prepreg comprising:

30 forming a continuous web material comprising a layer of fibrous material between two films of curable resin;

conveying the web material along a travel path and through at least one moving pressure nip formed between a moving pressure roller and a moving supporting surface,

wherein the moving pressure roller and the moving supporting surface travel at different velocities relative to each other resulting in a relative velocity V_{rel} between the web material and the pressure nip, and

wherein the at least one moving pressure nip travels in the same direction as the web material while applying sufficient pressure to compress the web material and to affect impregnation of the fibrous material with the curable resin.

In some embodiments, the at least one moving pressure nip applies a pressure-at-time of up to 10 MPa•s to affect full impregnation, and

pressure-at-time is defined as P/V_{rel} where P is the linear force applied to the web material.

In some embodiments, the web material is conveyed through a plurality of moving pressures nips configured to establish a pressure-at-time of up to 10 MPa•s during impregnation.

In some embodiments, pressure-at-time is up to 7 MPa•s during impregnation.

In some embodiments, the web material is traveling at a velocity of 15 m/min or greater.

In some embodiments, the web material is traveling at a velocity of 100 m/min or greater.

In some embodiments, the moving support surface is provided by a rotating drum having an outer circumferential surface, the web material wraps around a portion of the drum's outer circumferential surface as the drum rotates during impregnation, and

the at least one moving pressure nip comprises a plurality of moving pressure nips, which are created by an endless roller chain of linking idler rollers revolving in a direction opposite to the rotational direction of the rotating drum while some idler rollers in the roller chain are pressed against a portion of the drum's circumferential surface and against the web material passing there between.

In some embodiments, prior to being conveyed through at least one moving pressure nip, the web material is heated to lower the viscosity of the curable resin so that the resin is in a molten state, and

after impregnation, the web material is cooled to increase the viscosity of the resin therein.

In some embodiments, heating of the web material is provided by a preheating roll located upstream from the rotating drum, along the travel path of the web material, and cooling of the web material is provided by a chill roll located downstream from the rotating drum.

In some embodiments, the curable resin comprises at least one thermoset resin as a major component.

In some embodiments, the layer of fibrous material comprises continuous, unidirectional fibers arranged parallel to each other with small spacing between adjacent fibers.

In some embodiments, the layer of fibrous material is in the form of a continuous, self-supporting fabric.

In some embodiments, the layer of fibrous material comprises fibers selected from the group consisting of:

glass fibers, carbon fibers, graphite fibers, aramid fibers, polyamide fibers, high-modulus polyethylene (PE) fibers, polyester fibers, poly-p-phenylene-benzoxazole (PBO) fibers, boron fibers, quartz fibers, basalt fibers, ceramic fibers, and combinations thereof.

A second aspect of the present invention provides a prepreg fabrication system comprising:

a fiber supply unit for supplying a continuous layer of fibrous material;

means for supplying a first resin film and a second resin film;

means for placing the first resin film on one surface of the layer of fibrous material and means for placing the second resin film on an opposite surface of the layer of fibrous material so that the fibrous material is sandwiched between the first and second resin films; and

an impregnation zone downstream from the means for placing the first and second resin films onto the layer of fibrous material, the impregnation zone comprising:

(i) a movable support surface for supporting a web material during impregnation;

(ii) an endless roller chain carrying a plurality of linking, rotatable idler rollers, a portion of the roller chain facing the movable support surface;

(iii) pressure applicators for pressing at least some of the idler rollers facing the support surface against the support surface to form pressure nips; and

(iv) means for conveying a web material along a travel path and through the pressure nips,

wherein the movable support surface is configured to move at a first velocity during operation and the roller chain is configured to revolve at a second velocity different from the first velocity so as to establish a relative velocity between

the revolving roller chain and the moving support surface, and wherein the relative movements of the support surface and the roller chain create pressure nips that are moving in the same direction as the moving direction of the support surface.

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In some embodiments, the movable support surface is provided by a rotatable drum, which is configured to rotate in a rotational direction opposite to the rotational direction of the roller chain.

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In some embodiments, the system comprises a chamber which encloses the endless roller chain and the rotatable drum.

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In some embodiments, the impregnation zone further comprises a pre-heating roll located along the travel path of the web material and upstream from the pressure nips for heating the web material prior to impregnation, and a chill roll located downstream from the pressure nips for cooling the web material after impregnation.

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In some embodiments, a chamber encloses the endless roller chain, the rotatable drum, the pre-heating roll, and the chill roll, wherein the chill roll is located in a thermally-isolated compartment within said chamber.

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In some embodiments, the continuous layer of fibrous material comprises continuous, unidirectional fiber filaments arranged parallel to each other with small spacing between adjacent fibers.

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In some embodiments, the fiber supply unit comprises:
at least one creel which supports a plurality of spools around which continuous fiber bundles are wound, each fiber bundle comprising a plurality of fiber filaments, and

a fiber spreading unit located downstream from the at least one creel, the fiber spreading unit being configured to spread the fiber bundles into continuous, unidirectional fiber filaments.

In some embodiments, the fiber supply unit is equipped to supply a continuous, self-supporting fabric as the continuous layer of fibrous material.

In some embodiments, the system further comprises a winding up section located downstream from the impregnation zone for winding up the web material exiting the impregnation zone.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates the general concept of Relative Speed Impregnation technique according to the present disclosure.

FIG. 2 illustrates a conventional technique of applying static pressure nip to affect impregnation.

FIG. 3 is a graph showing the relationship between pressure-at-time and relative velocity (V_{rel}) between a moving web material and the pressure nip applied during impregnation.

FIG. 4 shows an embodiment of a prepreg fabrication system.

FIG. 5 shows an embodiment a static pressure applicator for pressing an idler roller against a web material.

FIG. 6 shows another embodiment of a static pressure applicator for pressing an idler roller against a web material.

FIG. 7 illustrates the roller chain progression under static pressure applicators according to an embodiment of applying pressure against a moving web material.

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DETAILED DESCRIPTION

Disclosed herein is a prepreg fabrication method with an improved resin impregnation technique - referred herein as relative speed impregnation (RSI). The impregnation technique disclosed herein is related to resin film impregnation in which at

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least one resin film is pressed against each of the top and bottom surfaces of a continuous fibrous web to produce a continuous prepreg, in which the fibrous material is embedded within a matrix resin. The fibrous web is composed of reinforcement fibers and may be in the form of unidirectional fibers or a fabric (woven or nonwoven). The term "impregnate" as used herein refers to the introduction of a curable matrix resin to reinforcement fibers so as to partially or fully encapsulate the fibers with the matrix resin.

An objective of the RSI technique is to produce the fastest prepreg production speed with the least fiber bed distortion and minimum pressure to achieve a desired impregnation level. To that end, an impregnation zone configuration is designed so that a web of resin-fiber material moving at a first velocity (V_w), often called "line speed," through an impregnation zone while pressure is applied by at least one moving pressure nip moving at a second velocity (V_n) and in the same direction as that of the moving web. The moving pressure nip is formed between a moving pressure roller and a moving surface supporting the web material. The moving surface is configured so as to mitigate the friction forces to the contacting surface of the web material. According to a preferred embodiment, the moving surface is part of a rotating drum with a relative large cross-sectional diameter. V_w and V_n are the operating velocities relative to a fix point on the ground. V_w is different from V_n , whereby the difference between V_w and V_n is the relative velocity (V_{rel}) between the web material and the pressure nip. The level of impregnation is affected by the relative velocity (V_{rel}).

FIG. 1 illustrates the general concept of the RSI technique. In this figure, the web material W (composed of a layer reinforcement fibers sandwiched between two resin films) is moving at a line speed of 21 m/min while pressure is applied by the moving pressure nip formed between rollers 1 and 2, each roller rotating about its own central axis. The pressure nip is moving in the same direction as that of the web material W at a velocity of 18 m/min. This means that the relative velocity (V_{rel}) between the web material W and the moving pressure nip is 3 m/min. As such, the line speed (i.e. production rate) of the web material is

7 times that of the relative velocity (V_{rel}). The line speed speeds as discussed in the present disclosure may be measured using conventional speed sensing devices such as tachometers.

In contrast, conventional prepreg fabrication methods typically involve applying static pressure nip to affect impregnation as illustrated in FIG. 2. In **FIG. 2**, the pressure nip formed by rollers 1 and 2 is stationary (i.e., velocity is 0 m/min) as the web material is passing through the nip. In this case, the line speed of the web material is the same as the relative velocity (V_{rel}), and consequently, the line speed of the web material is limited to the relative speed (V_{rel}). As such, in order to achieve the same level of impregnation at V_{rel} of 3 m/min as in the RSI technique, the line speed of the web material is limited to 3 m/min.

The advantage of the RSI process is that the physics of impregnation is decoupled from the line speed of the web material, thereby enabling a significantly higher prepreg production rate at identical levels of impregnation as compared to conventional impregnation methods using static pressure nips or belts. These conventional methods generally require immense forces and complicated control systems.

In order to provide impregnation, pressure-at-time is required — the pressure applied to web material (not too high or too low) and time provided by slow speed. Pressure-at-time may be calculated as P / V_{rel} — the linear force (P) applied to the web material divided by the relative velocity (V_{rel}), and is measurable in units of Pascal-second ($\text{Pa}\cdot\text{s}$), equivalent to $\text{kg}/\text{m}\cdot\text{s}$. The linear force (P) is the downward force per linear width, e.g. pounds per inch (PLI) or Newtons per meter (N/m), exerted by the pressure roller (upper roller 1, FIG. 1), which is measured along the width of the web material. The relationship between pressure-at-time and relative velocity V_{rel} is hyperbolic as illustrated in **FIG. 3**. As V_{rel} is decreased, pressure-at-time dramatically increases. And the impregnation level goes up with pressure-at-time. As such, it is desirable to keep V_{rel} as low as possible. The optimum V_{rel} is

dependent on the resin properties (e.g. viscosity) and permeability of the fiber web (e.g. openings or voids in the fiber layer, spacing/interstices between fibers, etc.).

According to a preferred embodiment, the RSI process is carried out by moving a web material (which is composed of a fiber layer sandwiched between two resin films) through an impregnation assembly having one or more moving pressure nips applying pressure-at-time of up to 10 MPa•s, or up to 7 MPa•s in certain embodiments, to achieve the required level of impregnation, e.g. up to 100% impregnation level. The pressure-at-time in this context refers to that applied by the entire impregnation assembly. The level of impregnation refers to how far the resin has penetrated through the thickness of the fiber layer. If the resin has penetrated through the entire thickness of the fiber layer, filling all interstices/gaps/openings therein, and there is substantially no resin-free region at the center of the fiber layer, then 100% or full impregnation has been achieved. Because impregnation is decoupled from the line speed of the web material, the line speed is limited only by the size of the manufacturing equipment. As an example, in conventional impregnation methods using static-nip arrangement, s-wraps, or pressure belts, the line speed of a high viscosity web material with a thick fiber bed may be up to 15 ft/min (3 m/min), while the RSI process is capable of increasing the line speed by more than 10 fold.

An embodiment of a prepreg fabrication system with means for implementing the RSI process is shown in **FIG. 4**. Referring to FIG. 4, the prepreg fabrication process starts with conveying continuous fiber bundles 11 from a fiber supply unit 10 to a fiber spreading section 12. The fiber supply unit 10 includes a plurality of spools for winding the fiber bundles and creels for supporting the spools. Each fiber bundle is composed of a plurality of fiber filaments. The fiber spreading section 12 is equipped with suitable means for spreading the fiber bundles before contacting the fibers with the resin films. As such, the spread fibers appear as a sheet of unidirectionally aligned fiber filaments with small spacing between adjacent filaments. Guide rollers are positioned along the traveling path of the fiber bundles to guide the fiber bundles and to provide the necessary tension therein. The

spread fiber filaments from the fiber spreading section 12 are then combined with an upper resin film 13a and a lower resin film 13b with the aid of rollers 14 so that the fiber filaments are sandwiched between the two resin films. Each resin film is supplied by its own supply roll and the surface that is not in contact with the fiber filaments is covered by a release paper. The resulting web material 15 is next conveyed through an impregnation zone 16, which includes an insulated chamber 17 enclosing a pre-heating roll 18, a rotating drum 19, an endless roller chain 20 of linking idler rollers, and a thermally-isolated, chill roll 21.

The pre-heating roll 18 is positioned at the beginning of the impregnation zone and upstream of the drum 19. Prior to entering the impregnation zone 16, the resin films are in a solid state and may be kept at a cold temperature during storage in order maintain their solidified state. Immediately after the web material 15 enters the chamber 17, the pre-heating roll 18 applies heat to the web material in an amount sufficient to decrease the resin viscosity so that the resin is softened but not high enough to cause substantial curing of the resin.

The chamber 17 is equipped with suitable temperature control mechanisms (not shown), for example, infra-red sensors mounted onto the sidewall of the chamber 17, to provide temperature data for the web material, the drum 19, the roller chain 20 as well as the tension of the web material entering and exiting the chamber 17. According to one embodiment, the temperature in chamber 17 may be maintained within the range of 50°C to 120°C, which is sufficient for most commercially available resin systems. During impregnation, the resin penetrates into the interstices/spacing between the fiber filaments. The resin viscosity is stabilized and maintained at a desired level as the web material travels through the entire impregnation zone with the aid of the temperature control mechanism in the chamber 17. According to one embodiment, the viscosity of the resin during impregnation is dependent upon the target resin system but may range from 0.03 Pa•s to 7000 Pa•s.

The drum 19 provides a moving support surface for the web material during impregnation and cooperates with the roller chain 20 to establish moving pressure nips through which the web material passes. The web material wraps around a portion of the drum's outer surface as the drum rotates. The large cross-sectional diameter of the drum 19 provides a physical platform for handling the nip pressures with the least amount of curvature possible. The roller chain 20 is configured to carry a series of closely spaced, idler rollers having elongated, cylindrical bodies with lengths extending transversely to the travel direction of the web material, each idler roller being freely rotatable about its own axis. The idler rollers are linked to each other by suitable linking mechanisms, for example, each idler roller may have a pin (a connecting mechanism) at one axial end connected to a corresponding link in an endless chain of connecting links. The roller chain 20 is caused to revolve by a suitable chain drive. The number of idler rollers in the chain 20 may be varied depending on factors such as the required levels of force and web pressure, the desired web width and commensurate deflection needs.

During operation, the roller chain 20 revolves in a direction opposite to the rotational direction of the drum 19 while some of the idler rollers in the roller chain 20 are pressed against a portion of the drum's outer surface and against the web material passing there between, thereby creating a plurality of pressure nips moving at velocity V_n . The rotational velocity of the drum 19, which is driven by a suitable drive motor, is equivalent to the line speed V_w of the web material as it moves through the impregnation zone 16, and the revolving velocity of the chain roller 20 is equivalent to the velocity V_n of the moving pressure nips. As such, the web material is being compressed by the outer circumferential surface of the rotating drum 19 and the moving idler rollers in the chain 20 to affect impregnation. As discussed above, the line speed V_w of the web material as it moves through the impregnation zone 16 is different from the velocity V_n of the moving pressure nips created by the drum 19 and the roller chain 20, such that a pre-determined relative velocity V_{rel} can be established, wherein $V_{rel} = V_w - V_n$. By this arrangement, a pressure-at-time of up to 10

MPa•s can be achieved. The pressure-at-time in this context refers to that applied by the pressure nips created between the drum 19 and the chain roller 20.

Still referring to FIG. 4, the chill roll 21 is located downstream from the drum 19 in a separate, thermally-isolated compartment, and is configured to lower the temperature of the web material sufficiently to increase the resin viscosity and lock in impregnation. The cooled, web material exiting the impregnation zone 16 is a prepreg 22 with a set thickness and solidified resin component. After the prepreg 22 exited the impregnation zone 16, the release paper 23 on one side of the prepreg 22 is peeled off, and then the prepreg 22 is taken up by a winding roll 24.

The mechanisms for applying pressure load to the idling rollers as they come into contact with the outer surface of drum 19 may vary depending on the equipment design. Some examples are shown in **FIGS. 5 and 6**. FIG. 5 shows an embodiment for pressing down onto a chain link connected to the idler roller in the roller chain 20 using a static pressure applicator. Referring to **FIG. 5**, one of the idler rollers 51 in the roller chain 20 is shown to have a shaft idler 51a at its axial end connected to a corresponding link 52, which is part of an endless link chain. The static pressure applicator includes a piston 53 connected to a pressure roller 54 so as to drive the movement of the pressure roller 54 either up or down. The pressure roller 54 is freely rotatable about its own axis and is configured to move in and out of engaging contact with the chain link 52. The piston 53 is positioned above the pressure roller 54 and is controlled to provide the necessary pressure downward onto the chain link 52 or to release the pressure.

FIG. 6 shows an embodiment for pulling down onto the chain link connected to the idler roller using a static pressure applicator. In this embodiment, the pressure roller 54 for engaging the chain link 52 is connected to piston 55 via extension arm 56 positioned below the idler roller 51. The movement of the pressure roller 54 together with extension arm 56 is

driven by the piston 55. By this arrangement, the pressure roller 54 can be pulled down into engaging contact with or lifted away from the chain link 52 by the piston 55.

A plurality of pressure applicators of the type shown in FIG. 5 or FIG. 6 may be positioned adjacent to the section of the roller chain 20 that faces the drum 19 so as to engage each idler roller in the roller chain 20 that comes into contact with the web material passing between the roller chain 20 and the drum 19, or only selected contacting idler rollers (e.g. every other idler roller).

FIGS. 7A-7C show the roller chain progression in an embodiment in which an array of static pressure applicators (of the type shown in FIG. 5) cooperates with the roller chain 20 to apply pressure over the drum 19 such that the pressure experienced by the chain idler rollers smoothly transitions from one idler roller to the next. Each of FIGS. 7A-7C represents a snapshot at different time in the roller chain progression.

For measuring the load on the idler rollers disclosed herein, load cells can be employed, or hydraulic/pneumatic pressures can be derived from the loading systems of the rollers.

It should be understood that various modifications of the fabrication system shown in FIG. 4 are contemplated. In an alternative embodiment, the creel-containing unit 10 and the spreader section 12 are replaced by mechanisms for supplying a continuous, self-supporting fabric web. The self-supporting fabric web may be a woven fabric or a non-woven fabric (e.g. non-crimp fabric) composed of reinforcement fibers.

Furthermore, FIG. 4 depicts a two-film impregnation method, in which an upper resin film and a lower resin film are pressed against the top and bottom surfaces of the fiber web, respectively, so that the fiber web is sandwiched between the two resin films. However, it should be understood that the same fabrication system can be modified to incorporate additional resin films for impregnation. As an example, an additional impregnation zone may

be added downstream from the impregnation zone 16 and additional resin films may be applied onto both the upper surface and the lower surface of the impregnated web material exiting from the impregnation zone 16, in the same manner for applying the resin films 13a and 13b, but with the removal of the release papers from both sides of the web material exiting from the impregnation zone 16.

The RSI process disclosed herein decouples resin infiltration rate (pressure, viscosity and time limitations) from production rate by moving the pressure points (i.e. nips) with the web material such that the web material experiences longer time at pressure even though the web material and nips are moving fast. The use of a rotatable drum as shown in FIG. 4 instead of a second belt or a flat plate as known in the prior art mitigates the difficulties associated with upper and lower roll alignment and static plate friction which would rip apart the paper.

The reinforcement fibers for fabricating the prepregs may take the form continuous fibers, tows, or self-supporting woven or non-woven fabrics. Fiber structures may comprise a plurality of tows, each tow composed of multiple filaments, e.g. 3-12 thousands of filaments. The non-woven fabrics may include non-crimp fabrics in which the tows may be held in position by cross-tow stitches, weft-insertion knitting stitches, or a small amount of resin binder, such as a thermoplastic resin.

The fiber material includes, but are not limited to, glass (including Electrical or E-glass), carbon, graphite, aramid, polyamide, high-modulus polyethylene (PE), polyester, poly-p-phenylene-benzoxazole (PBO), boron, quartz, basalt, ceramic, and combinations thereof. For the fabrication of high-strength composite materials, e.g. for aerospace and automotive applications, it is preferred that the reinforcing fibers have a tensile strength of greater than 3500 MPa.

Generally, the matrix resin for impregnating the reinforcement fibers is based on a curable resin system containing thermoset or thermoplastic resins as the major component

in combination with minor amounts of additives such as curing agents, catalysts, co-monomers, rheology control agents, tackifiers, rheology modifiers, inorganic or organic fillers, thermoplastic or elastomeric toughening agents, stabilizers, inhibitors, pigments/dyes, flame retardants, reactive diluents, and other additives well known to those skilled in the art for modifying the properties of the resin matrix before or after curing.

The thermoset resins may include, but are not limited to, epoxy, unsaturated polyester resin, bismaleimide, polyimide, cyanate ester, phenolic, etc. In one embodiment, the resin matrix is an epoxy-based resin formulation which contains one or more multifunctional epoxy resins (i.e. polyepoxides) as the main polymeric component.

Suitable epoxy resins include polyglycidyl derivatives of aromatic diamine, aromatic mono primary amines, aminophenols, polyhydric phenols, polyhydric alcohols, polycarboxylic acids. Examples of suitable epoxy resins include polyglycidyl ethers of bisphenols such as bisphenol A, bisphenol F, bisphenol S and bisphenol K; and polyglycidyl ethers of cresol and phenol based novolacs.

The addition of curing agent(s) and/or catalyst(s) may increase the cure rate and/or reduce the cure temperatures of the matrix resin. The curing agent for thermoset resins is suitably selected from known curing agents, for example, guanidines (including substituted guanidines), ureas (including substituted ureas), melamine resins, guanamine derivatives, amines (including primary and secondary amines, aliphatic and aromatic amines), amides, anhydrides (including polycarboxylic anhydrides), and mixtures thereof.

The matrix resin may include toughening agents such as thermoplastic and elastomeric polymers, and polymeric particles such as core-shell rubber particles, polyimide particles, and polyamide particles. The matrix resin may also include inorganic fillers such as fumed silica quartz powder, alumina, and platy fillers such as mica, talc or clay (e.g., kaolin).

To form the resin films for prepreg fabrication, the matrix resin may be prepared in liquid form and then coated onto a release paper (i.e. carrier) to form a film of suitable areal weight. After drying, the resin film is then wound up onto a supply roll.

Example

As an example, a prepreg with width of 12.5 in may be made by impregnating a layer of unidirectional carbon fibers with epoxy-based resin films (e.g. CYCOM 977-3 from Cytec Industries Inc.; film areal weight of 35 gsm per side) using the impregnation system shown in FIG. 4 based on the following parameters:

Line speed = 15 m/min (or 50 fpm)

Pressure-at-time = 7 MPa•s

Temperature at pre-heating roll = 120°C

Resin viscosity during impregnation = 3000 cP

Temperature at chill roll = 25°C

The claims defining the invention are as follows:

1. A method of impregnating a fibrous material with a curable resin to form a prepreg comprising:

5 forming a continuous web material comprising a layer of fibrous material between two films of curable resin;

conveying the web material along a travel path and through at least one moving pressure nip formed between a moving pressure roller and a moving supporting surface,

10 wherein the moving pressure roller and the moving supporting surface travel at different velocities relative to each other resulting in a relative velocity V_{rel} between the web material and the pressure nip, and

15 wherein the at least one moving pressure nip travels in the same direction as the web material while applying sufficient pressure to compress the web material and to affect impregnation of the fibrous material with the curable resin.

2. The method of claim 1, wherein the at least one moving pressure nip applies a pressure-at-time of up to 10 MPa•s to affect full impregnation, and

20 pressure-at-time is defined as P/V_{rel} , where P is the linear force applied to the web material.

25 3. The method of claim 2, wherein the web material is conveyed through a plurality of moving pressures nips configured to establish a pressure-at-time of up to 10 MPa•s during impregnation.

30 4. The method of claim 2 or 3, wherein pressure-at-time is up to 7 MPa•s during impregnation.

5. The method according to any one of the preceding claims, wherein the web material is traveling at a velocity of 15 m/min or greater.

5 6. The method according to any one of the preceding claims, wherein the web material is traveling at a velocity of 100 m/min or greater.

10 7. The method according to any one of the preceding claims, wherein

the moving support surface is provided by a rotating drum having an outer circumferential surface, the web material wraps around a portion of the drum's outer circumferential surface as the drum rotates during impregnation, and

15 the at least one moving pressure nip comprises a plurality of moving pressure nips, which are created by an endless roller chain of linking idler rollers revolving in a direction opposite to the rotational direction of the rotating drum while some idler rollers in the roller chain are pressed against a
20 portion of the drum's circumferential surface and against the web material passing there between.

8. The method according to any one of the preceding claims, wherein,

25 prior to being conveyed through at least one moving pressure nip, the web material is heated to lower the viscosity of the curable resin so that the resin is in a molten state, and

30 after impregnation, the web material is cooled to increase the viscosity of the resin therein.

9. The method of claim 8, wherein heating of the web material is provided by a preheating roll located upstream from the

rotating drum, along the travel path of the web material, and cooling of the web material is provided by a chill roll located downstream from the rotating drum.

5 10. The method according to any one of the preceding claims, wherein the curable resin is in comprises at least one thermoset resin as a major component.

10 11. The method according to any one of the preceding claims, wherein the layer of fibrous material comprises continuous, unidirectional fibers arranged parallel to each other with small spacing between adjacent fibers.

15 12. The method according to any one of the preceding claims, wherein the layer of fibrous material is in the form of a continuous, self-supporting fabric.

20 13. The method according to any one of the preceding claims, wherein the layer of fibrous material comprises fibers selected from the group consisting of: glass fibers, carbon fibers, graphite fibers, aramid fibers, polyamide fibers, high-modulus polyethylene (PE) fibers, polyester fibers, poly-p-phenylene-benzoxazole (PBO) fibers, boron fibers, quartz fibers, basalt fibers, ceramic fibers, and combinations thereof.

25 14. A prepreg fabrication system comprising:

a fiber supply unit for supplying a continuous layer of fibrous material;

means for supplying a first resin film and a second resin film;

30 means for placing the first resin film on one surface of the layer of fibrous material and means for placing the second resin film on an opposite surface of the layer of fibrous

material so that the fibrous material is sandwiched between the first and second resin films; and

an impregnation zone downstream from the means for placing the first and second resin films onto the layer of fibrous

material, the impregnation zone comprising:

(i) a movable support surface for supporting a web material during impregnation;

(ii) an endless roller chain carrying a plurality of linking, rotatable idler rollers, a portion of the roller chain facing the movable support surface;

(iii) pressure applicators for pressing at least some of the idler rollers facing the support surface against the support surface to form pressure nips; and

(iv) means for conveying a web material along a travel path and through the pressure nips,

wherein the movable support surface is configured to move at a first velocity during operation and the roller chain is configured to revolve at a second velocity different from the first velocity so as to establish a relative velocity between the revolving roller chain and the moving support surface, and wherein the relative movements of the support surface and the roller chain create pressure nips that are moving in the same direction as the moving direction of the support surface.

15. The system of claim 14, wherein the movable support surface is provided by a rotatable drum, which is configured to rotate in a rotational direction opposite to the rotational direction of the roller chain.

16. The system of claim 15 further comprising a chamber which encloses the endless roller chain and the rotatable drum.

17. The system of claim 15 or 16, wherein the impregnation zone further comprises a pre-heating roll located along the travel path of the web material and upstream from the pressure nips for heating the web material prior to impregnation, and a
5 chill roll located downstream from the pressure nips for cooling the web material after impregnation.

18. The system of claim 17 further comprising a chamber which encloses the endless roller chain, the rotatable drum, the pre-
10 heating roll, and the chill roll, wherein the chill roll is located in a thermally-isolated compartment within said chamber.

19. The system according to any one of claims 14 to 18,
15 wherein the continuous layer of fibrous material comprises continuous, unidirectional fiber filaments arranged parallel to each other with small spacing between adjacent fibers.

20. The system according to any one of claims 14 to 19,
20 wherein the fiber supply unit comprises:

at least one creel which supports a plurality of spools around which continuous fiber bundles are wound, each fiber bundle comprising a plurality of fiber filaments, and

a fiber spreading unit located downstream from the at
25 least one creel, the fiber spreading unit being configured to spread the fiber bundles into continuous, unidirectional fiber filaments.

21. The system according to any one of claims 14 to 20,
30 wherein the fiber supply unit is equipped to supply a continuous, self-supporting fabric as the continuous layer of fibrous material.

22. The system according to any one of claims 14 to 21 further comprising a winding up section located downstream from the impregnation zone for winding up the web material exiting the impregnation zone.

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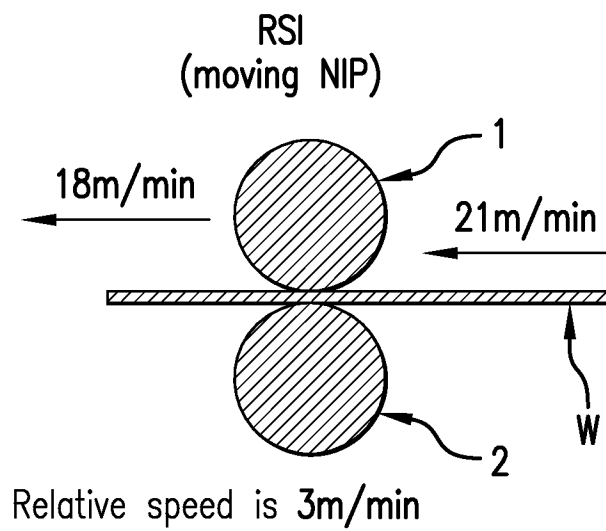


FIG.1

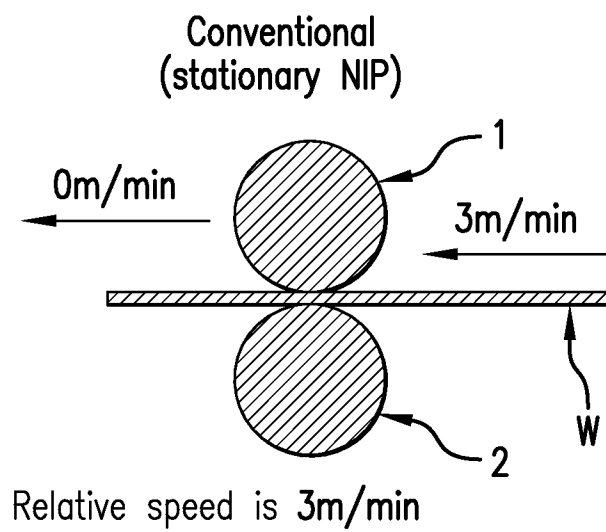


FIG.2

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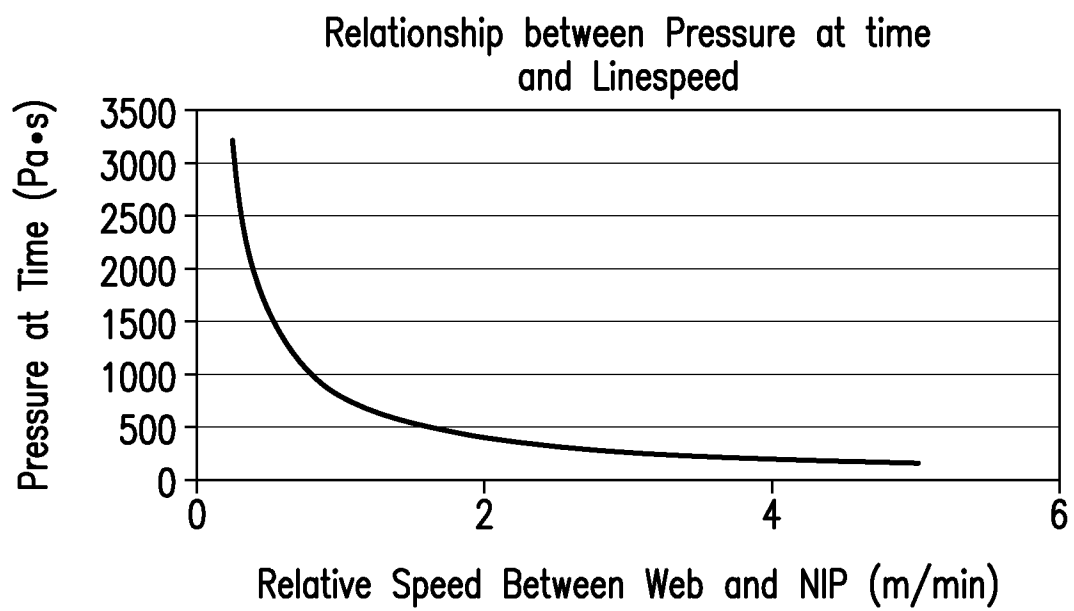


FIG.3

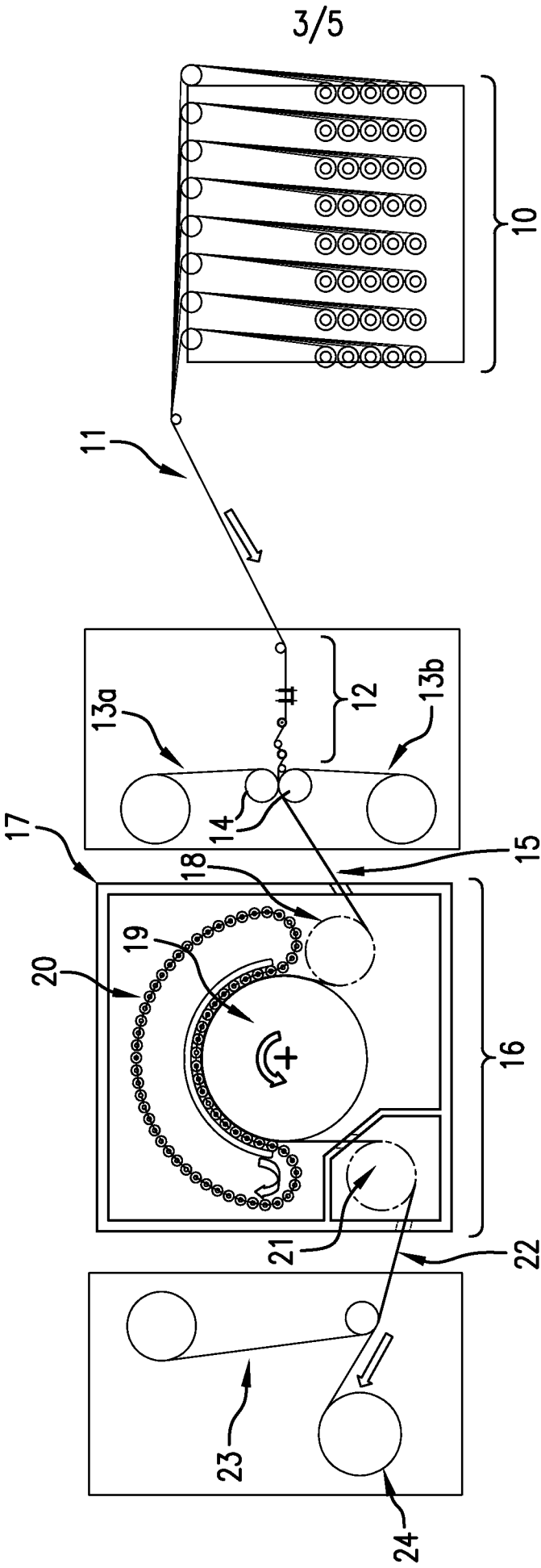
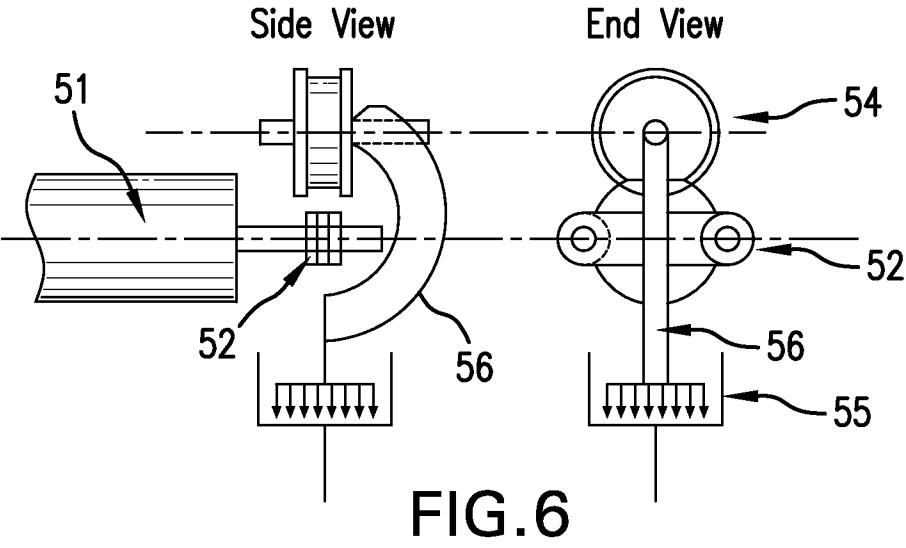
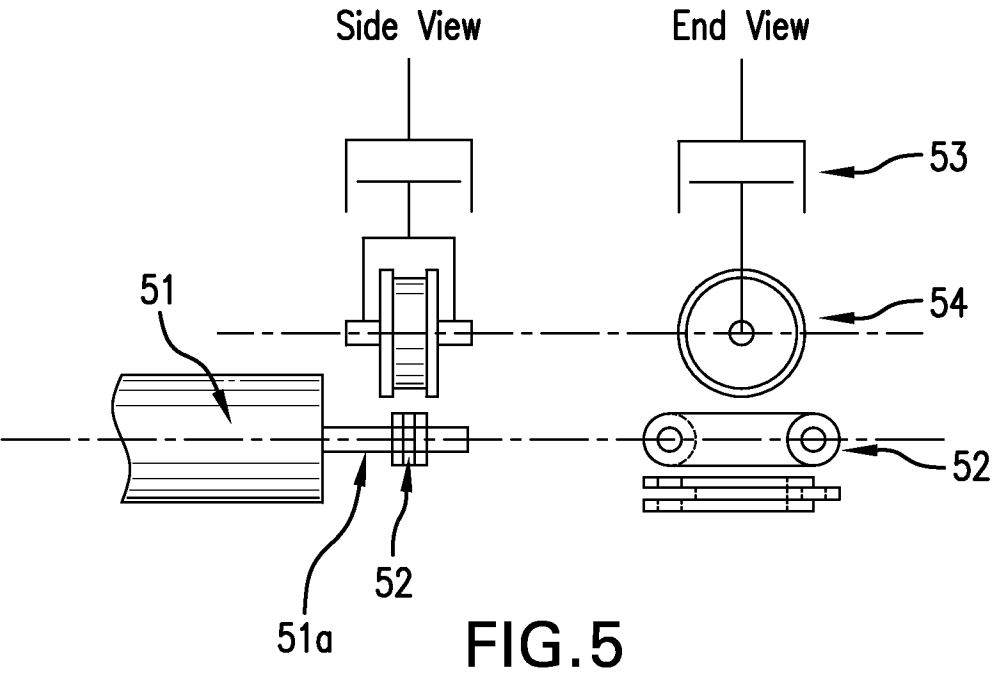


FIG. 4



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