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Thermoplastic Tape Winding with High Speed and at Quasi-Axial Pattern

Abstract

Filament winding is one of the most challenging technologies to produce axisymmetrical or even non-symmetrical structural thermoplastic composite shells with continuous fiber reinforcement.

Aims of this contribution are: a) to present results on laser assisted high speed filament winding of preimpregnated thermoplastic tapes and quasi axial helical filament winding with direct flame, and b) to compare different heating and preheating methods. Key-issue in the application of thermoplastic tape winding is the heating. Proper heating of preimpregnated tapes during the on-line winding process can be achieved by a variety of methods: laser and infrared radiation, hot gas and direct flame. It will be considered how the above heating methods affect the equipment and process costs, energy efficiency and response time.

Introduction

Thermoplastic composite materials offer the advantage of high fracture toughness, unlimited shelf life, recyclability, and continuous processing by avoiding the curing cycles which are characteristic for thermoset matrix composites. In addition to favourable mechanical properties thermoplastics offer a wide range of manufacturing options. Recent interest in advanced thermoplastic composites has been spurred by the promise of higher manufacturing productivity, increased quality and improved material properties.

Filament winding thermoplastic composite materials offers cost and performance advantages compared to conventional thermoset filament winding.

Key-factor in the successful application of thermoplastic winding technology is the heating system. During the consolidation process, matrix flow occurs until interlaminar contact is achieved. This process mainly depends on temperature, pressure and time. Many techniques can be found in the literature, raising matrix temperature above the melting point to achieve in-situ consolidation. This paper describes methods using direct flame and laser energy as heat sources. The required pressure is generated by tape tension.

THERMOPLASTIC COMPOSITE TAPE

	Advantages	Disadvantages
Processing	• short cycle time • weldability, ease of repair • easy quality control • post formable	• on-line heating • high viscosity • difficult to drape
Material	• high impact toughness • unlimited shelf life • fire resistant, low smoke • recycling possible	• high cost • creep behaviour • solvent sensitivity (amorphous types)

Figure 1: Advantages and disadvantages of filament winding unidirectional thermoplastic preimpregnated composite tape.

In-situ (on-line) processing of thermoplastic composite materials has the potential to overcome the drawbacks of conventional filament winding. It offers the option to achieve consolidation during the process which eliminates the need of post consolidation processing. Studies found that thermoplastic filament winding can be more cost effective than thermoset winding. Figure 1 gives an overview on advantages and disadvantages of filament winding unidirectional preimpregnated composite tape. To improve cost-effectiveness of thermoplastic filament winding it is necessary to obtain high material throughput rates in combination with constant quality.

High Speed Filament Winding

High speed filament winding has been achieved by processing thermoplastic preimpregnated tapes with laser radiation using an industrial scale high velocity, four axis winding device. The used numerical controlled traversing carriage machine is equiped with a very light support to minimize vibrations. Support speeds of 120 m/min can be attained with optimized control parameters.

The main task in heating preimpregnated thermoplastic tape by laser radiation is to focus the laser beam both on the incoming tape surface and the tape wound already on the mandrel. The design provides melting the tape surfaces in the contact zone. Figure 2 illustrates the applied principle for high speed laser filament winding. The set-up allows to reach winding speeds up to 120 m/min with options to get even higher speeds.

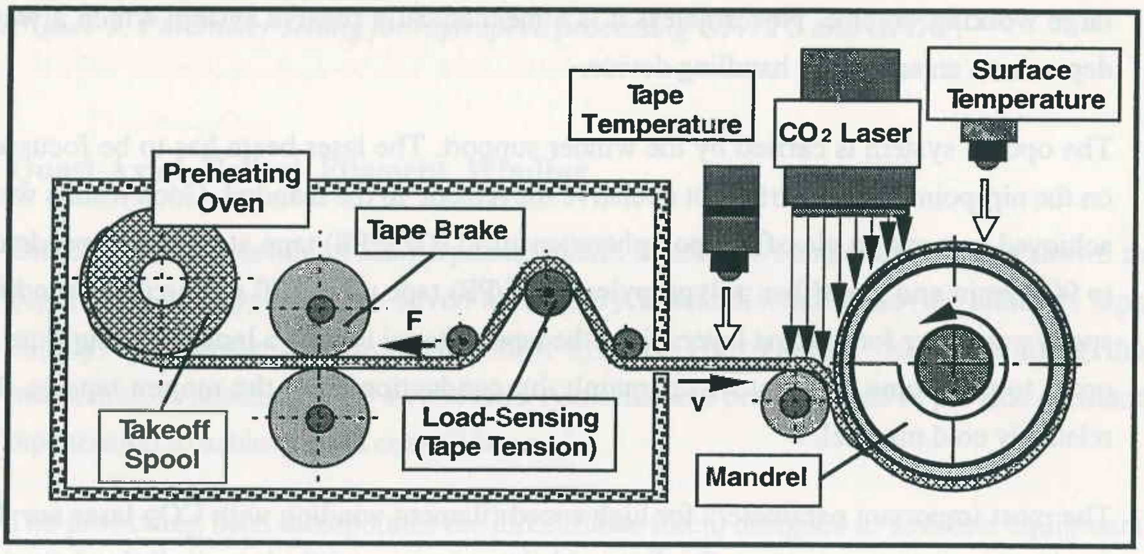

Figure 2: Laser processing set-up scheme. (F = tape-tension, v = winding speed)

The indicated high winding speed has been accomplished as follows:

- defocussing of the integrated high-performance CO_2 laser beam with 1.2kW energy output. The circular beam, decoupled from the resonator, is converted into an elliptical shape using a specular optical system with copper mirrors. The ratio of the minor axis to the major axis of the ellipse was at about 1:10, providing an optimum beam distribution.

- preheating of the incoming tape using a hot gas heated oven which can be purged by inert gas to prevent matrix degradation. The oven heats up the entire spool with the tape to be layed before reaching the winding head. The advantage of this system is the simplicity of temperature control. The tape temperature is constant even if the winding speed varies or the process interrupts.

The major advantage of laser radiation is the simple energy control (responding times of only a few milliseconds) in combination with a high radiation density. Overheating the tape can be avoided by taking the local tape temperature or the actual winding speed as the variable controlling the laser output.

An optical beam delivery systems is necessary to direct the radiation from the laser head to the working point (nip-point) on the mandrel. The best choice for CO_2 laser beam movement is an articulated arm. It is relatively light in weight and allows a comparatively large working volume. Nevertheless it is a mechanically passive system which always depends on an additional handling device.

The optical system is carried by the winder support. The laser beam has to be focussed on the nip-point which carries out a relative movement to the mandrel. Good results were achieved processing glassfiber polyphenylensulfid (GF/PPS) tape at winding speeds up to 90 m/min and glassfiber polypropylene (GF/PP) tape up to 120 m/min. The winding speed was lower for the first layers since the tape material needed a longer heating time in order to overcome the heat losses mainly by conduction from the molten tape to the relatively cold mandrel.

The most important parameters for high speed filament winding with CO_2 laser are the pre-heating oven temperature, the disposable laser power and the beam splitting between the tape surface which is being laid on the mandrel and the tape already wound in the vicinity. Pre-heating is required because of the large heat capacity of thermoplastic composites and the low transverse thermal conductivity which make it difficult to quickly heat the tape from room to processing temperature. After exiting the pre-heat oven, the tape passes into the final heating stage where it is brought to processing temperature. Optimized beam density and splitting rate is required to accurately raise the temperature of the tape. Figure 3 shows the adjusted parameter setting range for high speed processing GF/PPS and GF/PP.

HIGH SPEED FILAMENT WINDING

Winding Parameter	GF / PPS	GF / PP
Laser Power [W]	1200	1200
Winding Speed [m/min]	90	120
Oven Temperature [°C]	No Oven	110
Mandrel Temperature [°C]	23	23
Tape Tension [N/mm^2]	75	54
Beam Splitting [%] (Incoming Tape / Mandrel)	70 / 30	90 / 10

Figure 3: Parameter setting for high speed processing GF/PPS and GF/PP.

Quasi-Axial Helical Filament Winding

Direct flame processing of thermoplastic matrix filament wound composites is shown in Figure 4. The support of the seven axis gantry filament winding device contains tape supply, tape brake and process control system. The winding head, including the heatsource, is attached to the swivel axis. A mechanical brake is used to provide constant tape tension to achieve good consolidation.

The processing head incorporates the direct flame torch, designed as low cost equipment using commercial propane gas torches, providing the energy input to the tape achieving in-situ consolidation. In order to prevent matrix degradation if the winding process stops, the direct flame torch is attached to a pneumatic swivelling arm. The torch is in parking position during the process stops and turns into working position as soon as the winding process begins.

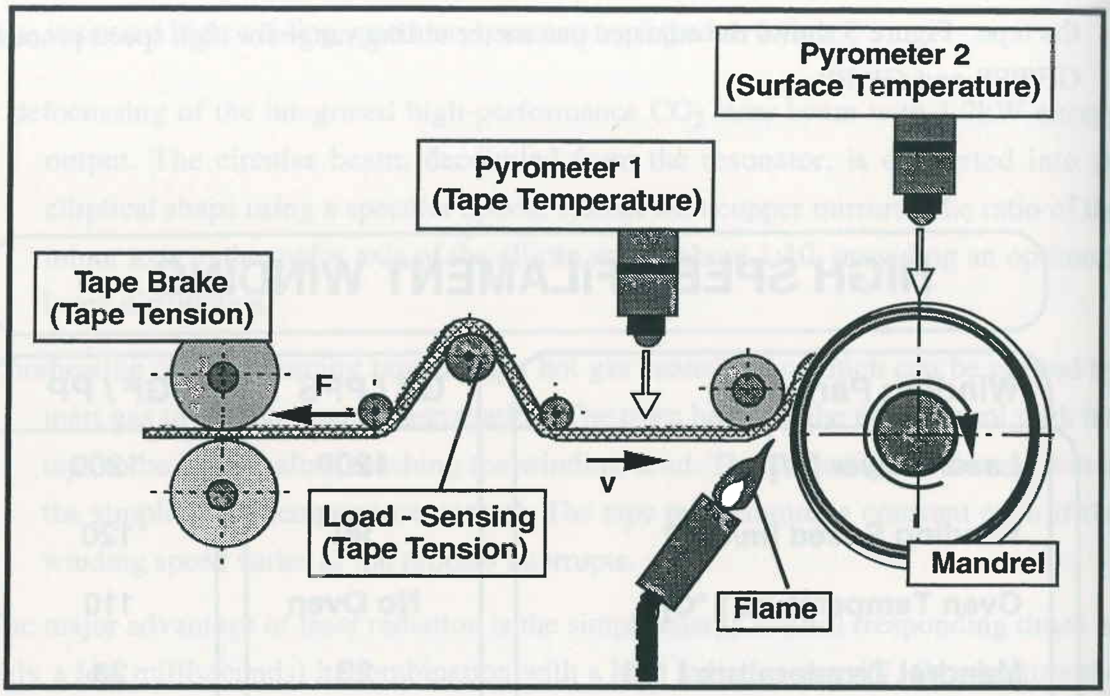

Figure 4: Direct flame processing set-up scheme. (F = tape-tension, v = winding speed)

The main objective is to generate an adequate meltzone of the thermoplastic matrix to obtain proper bonding between tape and consolidated laminate. This can be managed by focusing the flame and melting the matrix on the top surface of the laminate and the surface of the incoming prepreg tape simultaneously. The torch is directed exactly to the contact point .

Winding angles down to 17° were achieved using the described winding head. The pressure required to achieve good consolidation can usually be generated by tape tension or by direct mechanical force. Tension is relatively simple to use, but is adequate only within a certain range of mandrel diameters and winding angles. Pressure applied via rollers or sliding shoes requires accurate guidance. Since the described winding process involves no application of pressure to the tape during heating, a new concept was developed. The required pressure is generated using an improved post processing technique with compression belt (Figure 5). As experiments with this new process indicate, the consolidation of the tube samples and the surface quality are significantly improved.

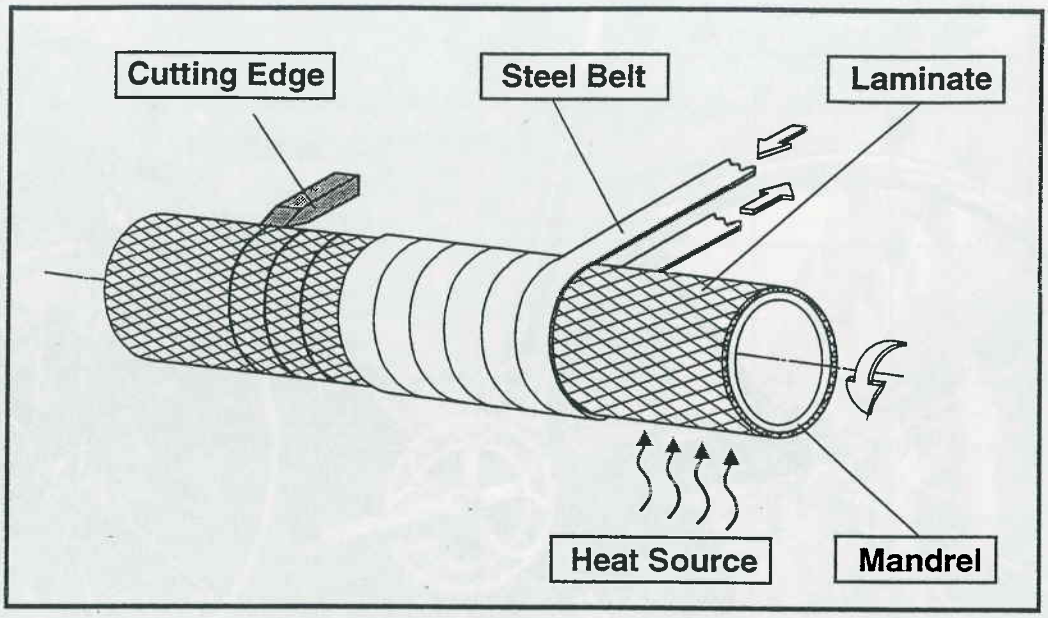

Figure 5: Post processing with compression belt.

The main advantages of post consolidation with compression belt are:

- no fiber displacement
- low cost machinery equipment
- no friction
- smooth surface

To demonstrate the feasibility of direct flame processing a CF/PA bicycle frame was designed and built, using several quasi axial filament wound tube geometries (Figure 6). Winding angles between 17° to 45° and tube diameters between 12mm and 48mm as well as eliptical shaped tubes were manufactured. The autoclaved CF/PA joints were then bonded to the tubes and aluminum inserts were added to the frame achieving a total weight of about 1000g.

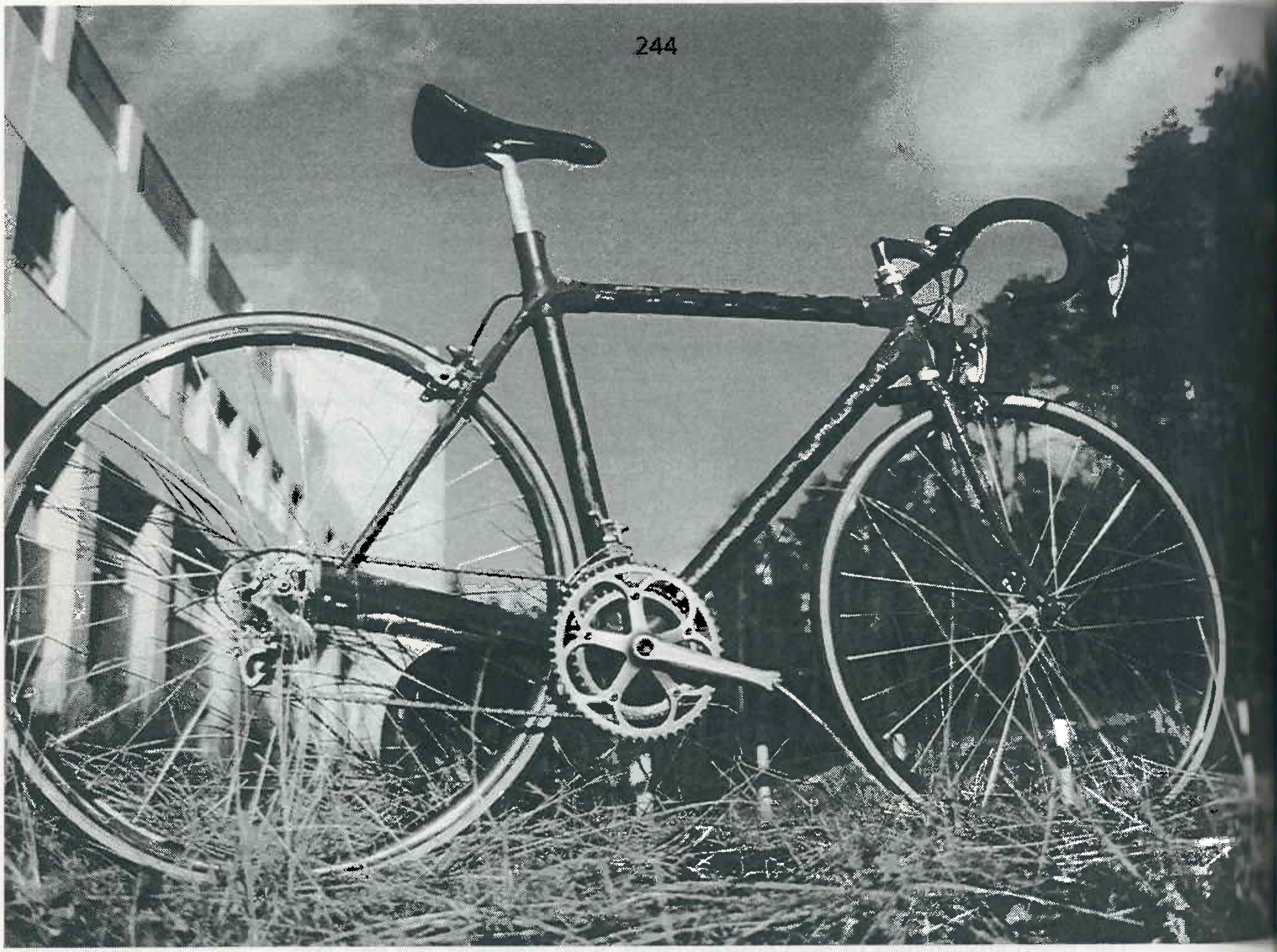

Figure 6: Thermoplastic filament wound bicycle frame.

Comparison of Heating Methods

Economics have a key function in the use of thermoplastic composites and in-situ consolidation. Laser radiation, infrared radiation, hot gas energy and direct flame processing are compared concerning purchase and process costs, winding speed, heat transfer, response time and winding path. Figure 7 summarizes differences in processing using the mentioned heat sources. Depending on part geometry, nature of load and piece number, each technology provides its advantages and disadvantages.

Laser technology provides the highest energy density and efficiency in the welding zone combined with fast response time. As discussed before, speeds up to 120 m/min were achieved for circumferential winding patterns. However, this technology is a very expensive option concerning purchase costs.

Infrared technology is inexpensive compared to laser technology. The energy density and response time is not nearly as high as with laser radiation.

Winding Technology	Costs		Processing				
	Purchase costs	Costs of process	Winding Speed	Increasing Tapewidth	Heat Transfer	Response Time	Windingpath Helical
Laser	450.000.-DM	Nd.-YAG 20.-DM/ h CO2 12.-DM/ h	60 - 140 m/min	difficult to realize	absorbtion local(spot)	very fast	critical
Infrared	10.000.-DM	1.-DM/ h	2.5 - 27 m/min	difficult to realize	absorbtion convection local(line)	fast	critical
Direct Flame	uncontrolled 7000.-DM controlled 60.000.-DM	20.-DM/ h	30 - 60 m/min	easy to realize	forced convection regional	short delay	unlimited
Hot-Gas	6000.-DM	nitrogen 20.-DM/ h air 1.50DM/ h	0.6 - 18 m/min	easy to realize	forced convection regional	short delay	unlimited

Figure 7: Comparison of heating methods.

Direct flame processing is a good choice for a heat source due to low purchase costs and high winding speed. As already discussed in this paper, helical winding patterns can be manufactured easily.

Compared to other heat sources, energy efficiency of hot-gas is very low. However, purchasing hot-gas heating systems is reasonable. Process costs increase significant if inert gas such as nitrogen must be used to prevent oxidation when high temperatures are needed.

Instead of using filament winding machines with several degrees of freedom, industrial robots can be used for filament winding as well. Loading or unloading the mandrel and quality control during the process can then also be achieved. Regarding the accuracy of articulated robots, they can not compare to cartesia winders.

Conclusion

This paper illustrates two important heating methods for processing thermoplastic composite tape. High winding speeds were achieved using laser assisted filament winding combined with a preheating oven.

A low cost direct flame winding head has been designed and manufactured. The anticipated performance concerning quasi axial winding patterns has been achieved. Several tube geometries with winding angles down to 17° were produced. Demonstrating the outstanding performance of this technology, a light weight carbon fiber bicycle frame was manufactured.

A comparison of winding technologies such as laser radiation, infrared radiation, hot-gas energy and direct flame processing concerning purchase and process costs, winding speed, heat transfer, response time and winding path is given. It is evident that every process has specific advantages. For example winding speeds up to 120 m/min can be achieved with laser radiation while process costs are lowerd using infrared energy. Processing various tape widths can be realized quite simply with hot gas torches and direct flames. These examples demonstrate that regarding winding pattern, working load and manufacturing scale a variety of winding technologies can be chosen. Even the experienced manufacturing industry has not yet agreed on a sophisticated thermoplastic winding philosophy.

Reference Index

/1/ R. Funck, F. Haupert, M. Neitzel, K. Friedrich
Fertigungsbedingte Eigenspannungen in gewickelten Bauteilen aus Thermoplast-Verbundwerkstoff
Kunststoffberater, Vol. 4/94

/2/ R. Funck, G. Scharr
Eigenspannungen in dickwandigen CFK-Kreisringscheiben sind beherrschbar
Kunststoffe 84 , Vol. 3, March 1994

/3/ C.E. Carpenter, J.S. Colton
On-line Consolidation Mechanisms in Thermoplastic Filament Winding (Tape Laying)
38th International SAMPE Symposium,May 10-13, 1993

/4/ I.Y. Chang, J. K. Lees
Recent Development in Thermoplastic Composites:
A Review of Matrix Systems and Processing Methods
Journal of Thermoplastic Composite Materials, p.277- 296, Vol.1, 1988

/5/ J.M. Charrier, M.E. Weber, X. Wang
Heating of Thermoplastic-Based Unidirectional Composite Prepreg Tapes
43rd Annual Conference of the Society of the Plastics Industry Inc., 1988

/6/ F. Ferraro, G. Di Vita, M. Marchetti, A. Cutolo, L. Zeni
Laser Processing of Thermoplastic Matrix Filament Wound Composites
Proceedings of the 4th European Conference on Composite Materials, 1990

/7/ M.B. Gruber
Thermoplastic Tape Laydown and Consolidation
Society of Manufacturing Engineers (SME), Technical Paper 1986

/8/ S.Y. Lee, G.S. Springer
Preheating Filament Wound Tows
36th International SAMPE Symposium, April 15-18, 1991

/9/ D. Hauber
Filament Winding with Thermoplastics
SME Technical Paper, EM87-552, 1987

/10/ K. Peters, G. Greening
Filament Winding of Preimpregnated Rovings
21st International SAMPE Technical Conference, 1989