PROCESSING RELATED CONSOLIDATION OF HIGH SPEED FILAMENT WOUND CONTINUOUS FIBER /THERMOPLASTIC COMPOSITE RINGS

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ABSTRACT: Filament winding of composite materials with thermoplastic matrices is more complicated then wet winding of thermosetting composites, due to the much higher viscosity of thermoplastics. Therefore, winding parameters have to be optimized in order to achieve both a good impregnation and high consolidation quality. In this study, the materials investigated were PET-powder impregnated and with a thin matrix sheath surrounded flexible glass fiber bundles. They offer a high degree of flexibility in comparison to stiffer tapes, but are much more difficult to process by a filament winding technique, hence a specially developed filament winding device for processing these flexible fiber bundles is presented. The filament winding technique is the so called in situ consolidation process, where the incoming yarn is welded onto the previously wound surface. The processing parameters in this winding process are mandrel temperature, preheating temperature, nip point temperature, tow tension, compaction force, and winding speed. For this technique, the winding parameters were optimized to obtain a bulk composite structure without any defects if possible. In order to characterize the consolidation quality, the composite's interlaminar shear strength was determined. Furthermore, the material's density, the flexural modulus, and residual stresses in the wound rings were measured.
From the economical point of view, it is very important to increase the winding speed. For this reason a hot air preheating zone was developed. The in-situ-consolidation-process obtained a further processing parameter: the preheating temperature. Winding speeds up to 30m/min were realized, by using this preheating zone, without diminishing a good consolidation quality.

INTRODUCTION

Polymeric composites are predestinated for low weight and high stiffness constructions. New developements have also focused at the use of thermoplastic matrices, because of their advantageous mechanical properties, especially the improved toughness. One possibility of manufacturing thermoplastic composites is filament winding. In the frame of this work, a thermoplastic filament winding arrangement was built up, especially for processing flexible fiber bundles. The winding process is called In-Situ-Consolidation Process.

In order to characterize the consolidation and impregnation quality, new material testing methods, especially for thermoplastic filament wound rings have been developed. The values of interlaminar shear strength [1], density, flexural modulus [2], and residual stresses are chosen as quality criteria.

An optimal processing window can be determined by systematically variing the different winding parameters .

DESCRIPTION OF WINDING EQUIPMENT

The possibility of welding thermoplastics enables the combination of two manufacturing steps, i. e. filament winding and consolidation, in one continuous production process. In the frame of this work a filament winding arrangement is presented, especially optimized for realizing winding speeds up to 30 m/min. During this process, the incoming yarn has to be melt impregnated and immediately consolidated onto the previously wound surface at the lay down point (nip point).

The in situ filament winding device is shown in Figure 1. A two axis motion controller coordinates the mandrel's rotation and the movement of the support to which the tow guidance system is attached. Hence, a predetermined fiber path can be realized. Tow tension can be measured and controlled. A defined compaction force can be applied by employing a compaction roller.

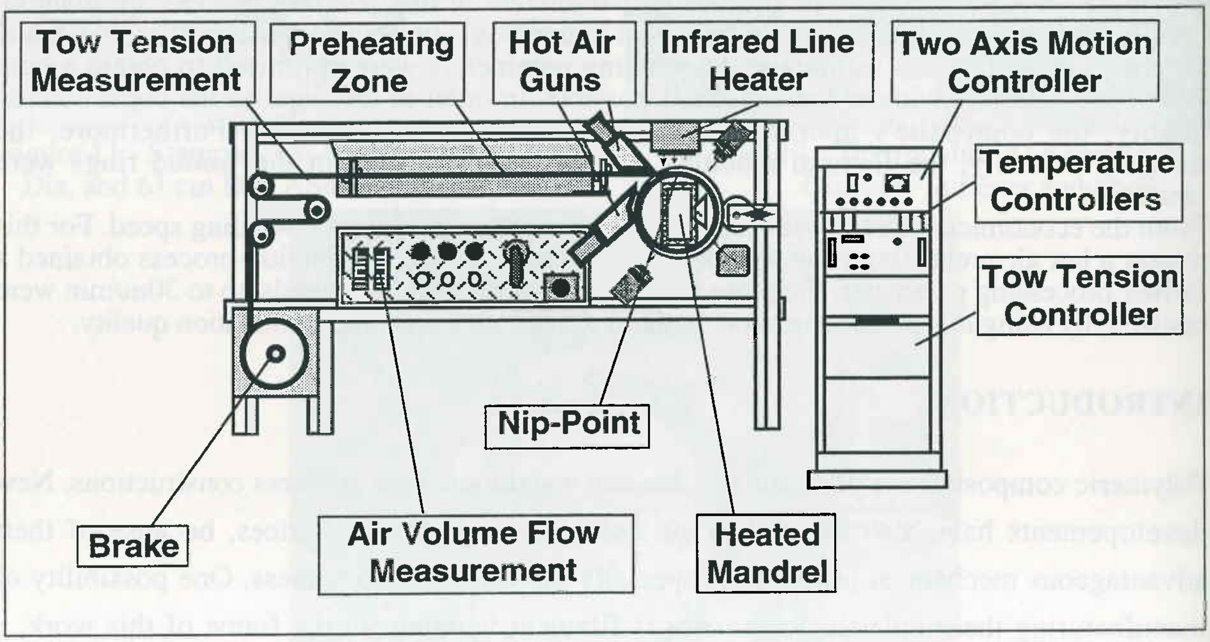

Figure 1: Thermoplastic filament winding device

The nip point heating device (Fig. 2) consists of two hot air guns, the first one is heating the incoming yarn, the second one the previously wound surface. An infrared line heater provides a constant nip point temperature. The mandrel temperature is also measured and controlled. In order to realize higher winding speeds, a preheating of the incomming tow is necessary. This preheating device consists of a hot air preheating zone.

Measurements of the ring surface temperatures are carried out by two pyrometers. The first is focused at the nip point, the second at the incoming surface of the wound part before reaching the hot air zone.

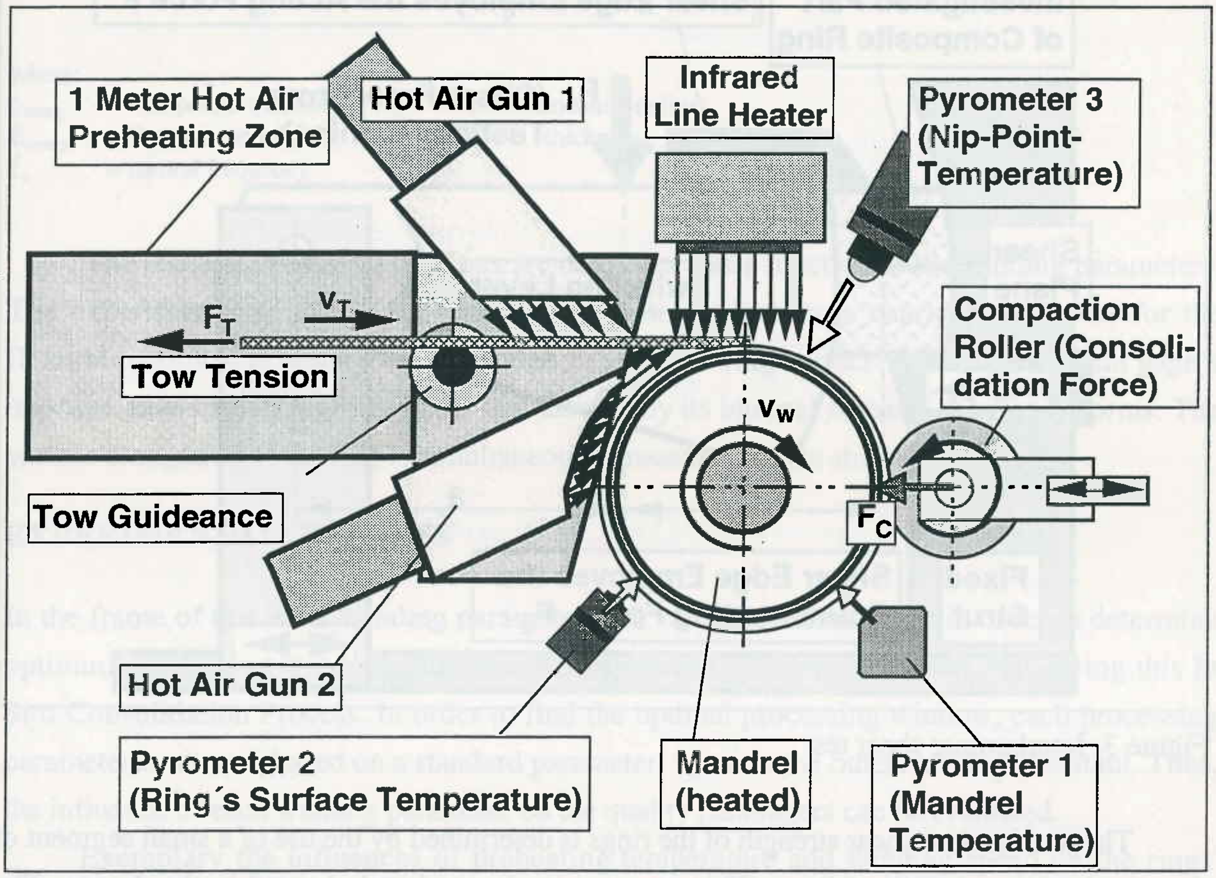

Figure 2: Nip point heating arrangement

In this arrangement the filament winding parameters are: winding speed (v_W), mandrel temperature (T_M), nip point temperature (T_{NP}), preheating temperature (T_{PH}), consolidation force (F_C), and tow tension (F_T).

MATERIALS INVESTIGATED

The materials investigated are powder impregnated fiber bundles. The matrix powder and the individual fibers are held together by a thin sheath of matrix material. In this study, the materials are glass fibers in polyethyleneterephthalate (GF-PET-1200tex).

MATERIAL TESTING METHODS

For the characterization of the impregnation and consolidation quality of the wound parts, suitable material parameters have to be selected, and testing methods have to be developed for their determination as well.

A new interlaminar shear testing device, which was recently developed by [1] is shown in Figure 3.

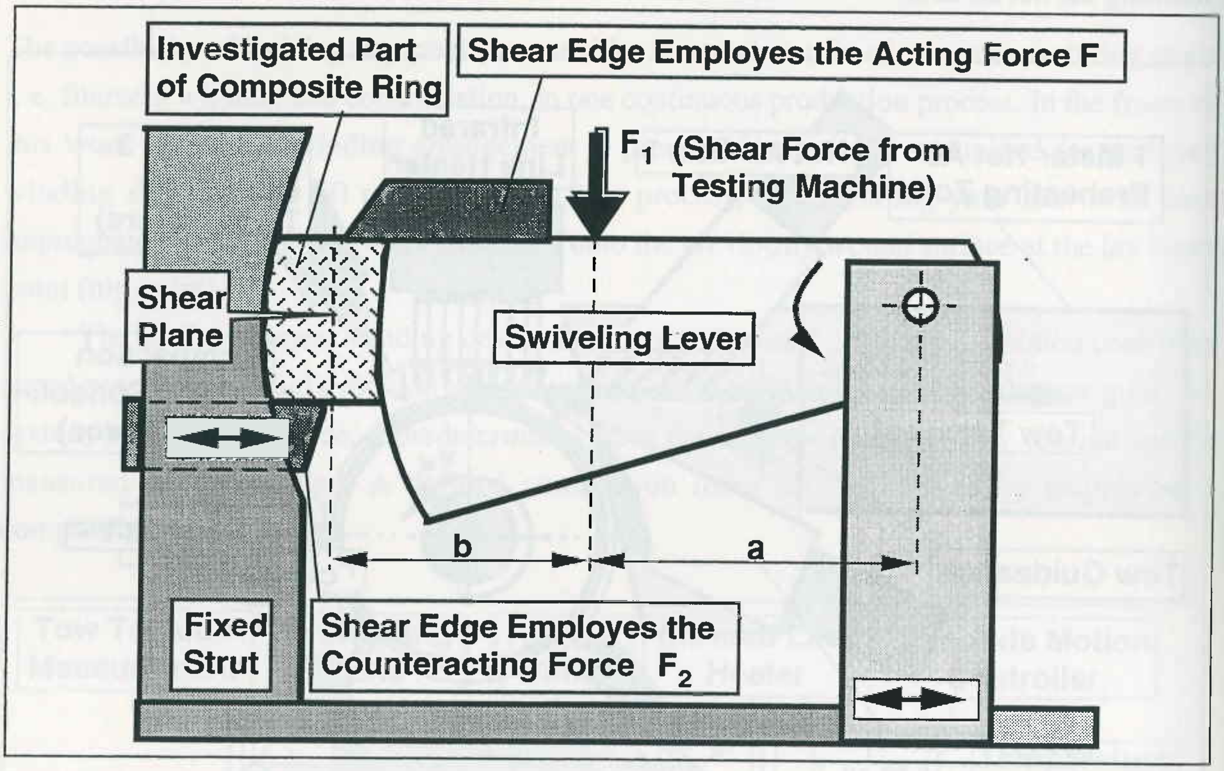

Figure 3: Interlaminar shear test

The interlaminar shear strength of the rings is determined by the use of a small segment of the ring having a length of 8mm. This segment is clamped and sheared in the device. The interlaminar shear strength can be calculated as:

$$\tau_i = \frac{1}{A} \cdot F_{1\,\max} \cdot \frac{a}{a+b} \qquad \text{(Eq.1)}$$

where:
τ_i = interlaminar shear strength
A = shear plane
$F_{1\,\max}$ = maximum shear force from testing machine
a,b = geometry of shear device (Fig.3)

The ring's density is also a very sensitive parameter for the characterization of the consolidation quality from thermoplastic filament wound structures. Because of the very simple geometry of a ring, the density can be easily calculated via the ring's dimensions and its weight.

The flexural modulus is investigated by a vibration test [2]. During this test, the natural frequency of the ring is determined. A strain gage is bonded on the inner surface of the ring and is connected via an amplifier to an oscilloscope. During this test, the ring is dropped on a hard surface. Once it is bouncing back, it starts vibrating in it´s natural frequency. The strain gage measures the elongation of the ring surface. With the frequency, the ring´s geometry and density, its flexural modulus can be calculated as shown in Equation 2 [3]:

$$E_{comp} = \rho_{comp} \cdot \left[\frac{R^2 \cdot f_n \cdot 2 \cdot \pi \cdot \sqrt{12}}{3 \cdot h} \right]^2 \qquad \text{(Eq.2)}$$

where:

ρ_{comp} = composite´s density
E_{comp} = flexural modulus
f_n = natural frequency

R = medium radius
h= thickness

The residual stresses in the rings are determined as a function of the winding parameters. The experimental setup for the residual stress determination is nearly the same as for the flexural modulus. A strain gage is bonded to the inner ring surface, while at the strain gage´s opposite side a small segment is cut out. Caused by its internal stresses, the ring deforms. The surface elongation of the ring is simultaneously measured by the strain gage.

EXPERIMENTAL RESULTS

In the frame of this work winding parameters are variied systematically in order to determine optimum processing windows for various fiber/matrix preforms manufactured during this In Situ Consolidation Process. In order to find the optimal processing window, each processing parameter is altered, based on a standard parameter, whereas the others are kept constant. Thus, the influence of each winding parameter on the quality parameters can be evaluated.

Exemplary the influences of preheating temperature and winding speed on the rings' quality are demonstrated.

The influence of preheating temperature on the processing quality of GF-PET (1200tex) is as follows (Fig. 4): With an increasing preheating temperature both the interlaminar shear strength and the density are improved.

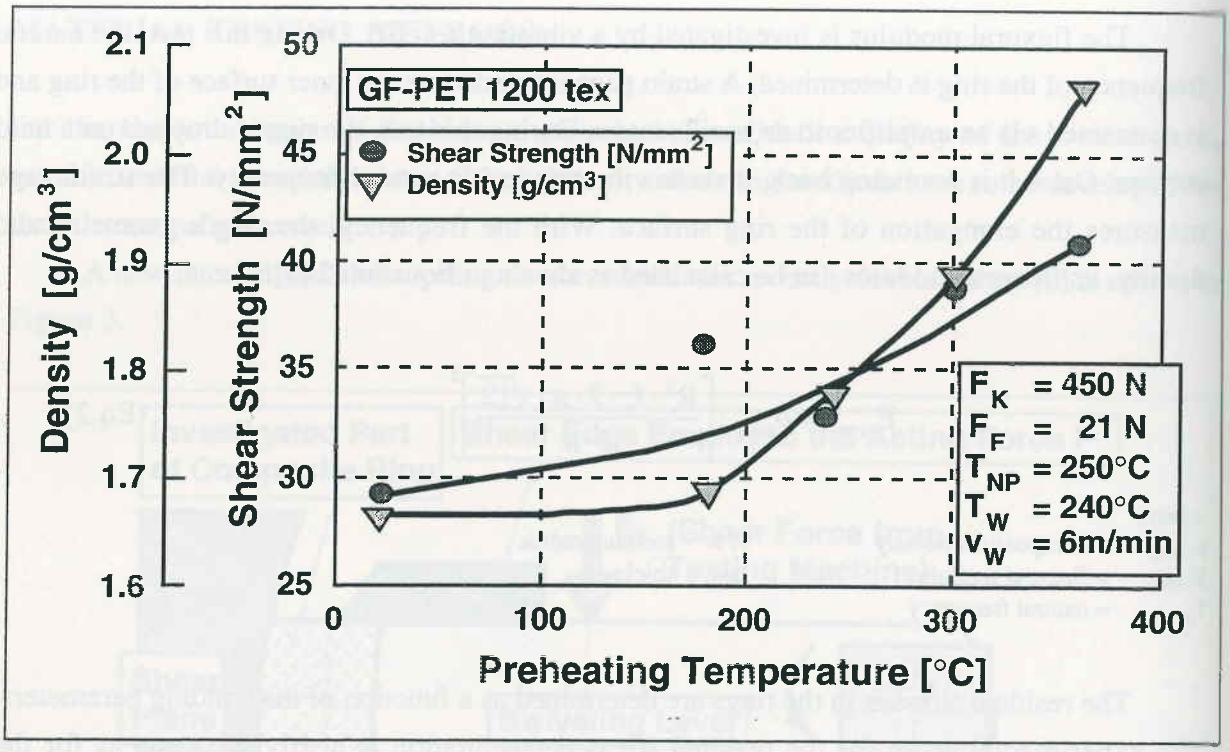

Figure 4: GF-PET 1200tex: Shear strength and density as a function of the temperature in the preheating zone. The latter is always higher than the actual temperature of the tow passing through it.

Higher preheating temperatures result in higher residual stresses up to a temperature of 250°C. In the range of 250°C to 360°C, the residual stress values are nearly constant (Fig. 5). A higher preheating temperature has a very positive influence on the ring's flexural modulus. The maximum moduli are reached for preheating temperatures of 360°C. Therefore, 360°C is the most suitable preheating temperature for processing GF-PET (1200tex). Higher preheating temperatures cause a deterioration of the matrix material. Lower temperatures do not allow a complete impregnation.

The next step in the frame of this work was an enhancement of the winding speed. Starting from the determined optimal processing parameters, the winding speed was increased in steps of 6m/min, in the range of 6m/min up to 30m/min. For higher winding speeds only a shorter time remains for the matrix material to melt and flow between the fibers.

Figure 6 exibits the ring's interlaminar shear strength as a function of winding speed. Higher winding speeds result in a lower interlaminar shear strength. Also the composite's density decreases with winding speed. These effects are due to the shorter impregnation time, and therefore a higher void content in the wound structures.

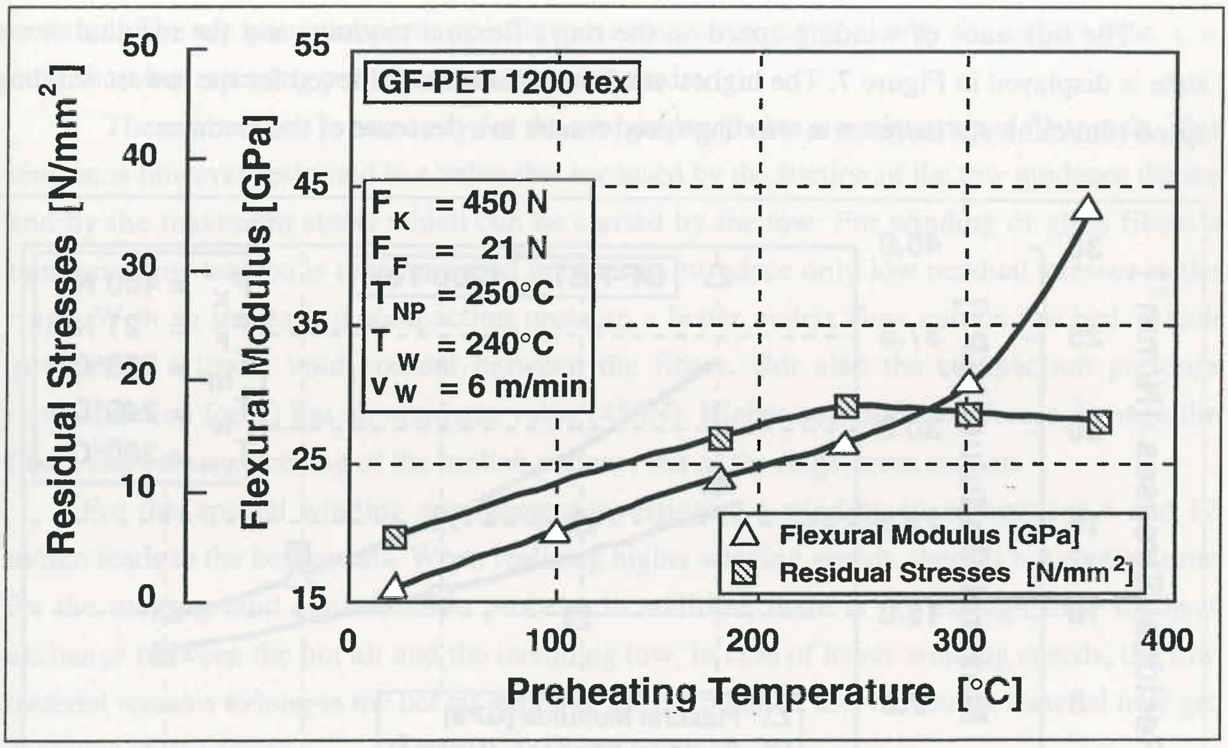

Figure 5: Flexural modulus and residual stresses as a function of preheating temperature

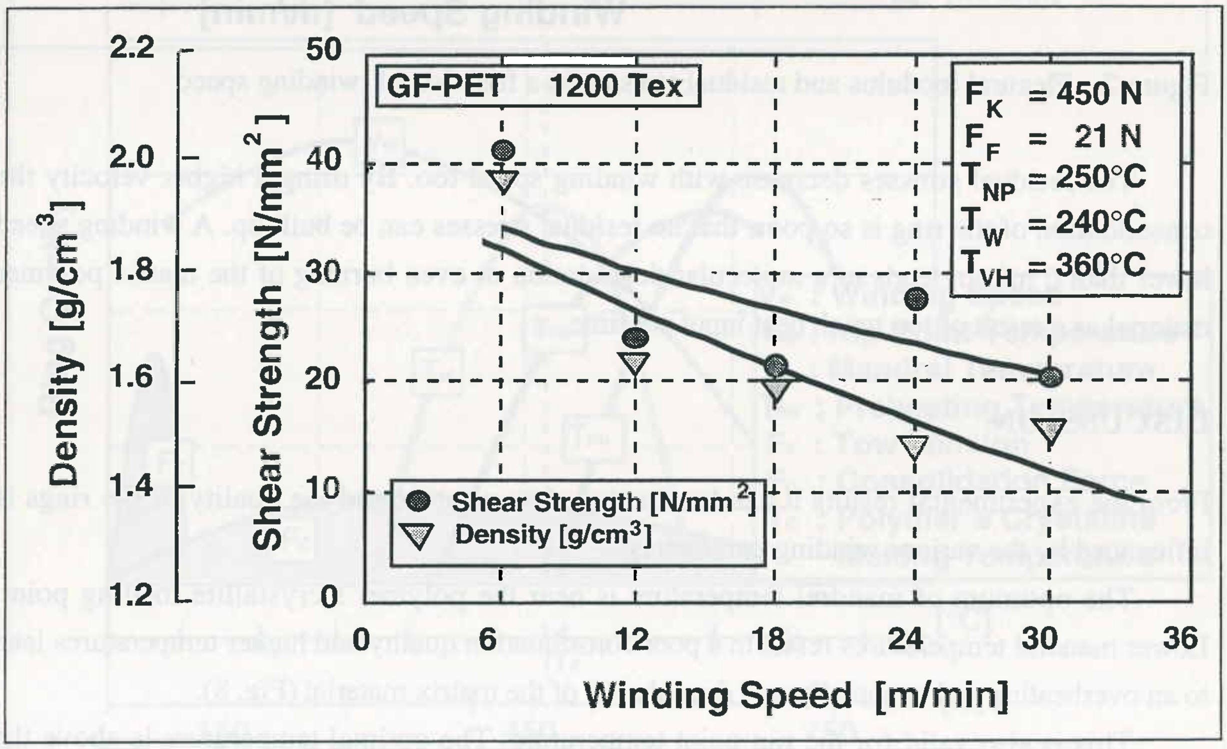

Figure 6: Shear strength and density as a function of winding speed

The influence of winding speed on the ring's flexural modulus and the residual stress state is displayed in Figure 7. The highest modulus values are achieved for the lowest winding speed (6m/min). An increase in winding speed results in a decrease of the modulus.

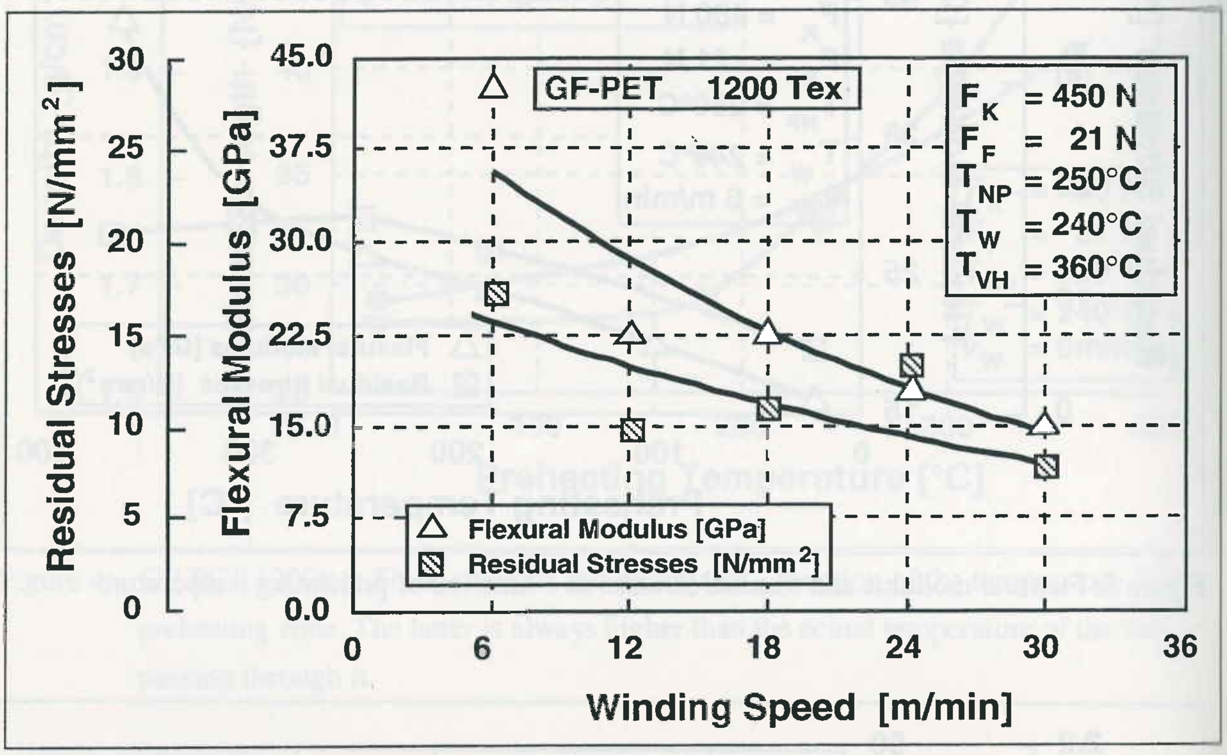

Figure 7: Flexural modulus and residual stresses as a function of winding speed

The residual stresses decrease with winding speed too. By using a higher velocity the consolidation of the ring is so poor, that no residual stresses can be built up. A winding speed lower than 6 m/min leads to a molecular degradation or even burning of the matrix polymer material as a result of too much heat input per time.

DISCUSSION

From the experimental results it can be concluded to what extend the quality of the rings is influenced by the various winding parameters.

The optimum of mandrel temperature is near the polymer´s crystallite melting point. Lower mandrel temperatures result in a poor consolidation quality and higher temperatures lead to an overheating and eventually to a degradation of the matrix material (Fig. 8).

This is also valid for the nip point temperature. The optimal temperature is above the crystallite melting temperature and above the mandrel temperature respectively, because the wound part is only instationary affected by heat in opposite to the stationary heating of the mandrel. The nip point temperature influences the matrix material only for a short time, i. e. only short but repeating periods of heat transition exist.

The tow tension is necessary for the tow guidance onto a predetermined fiber path. This tension is however restricted to a value that is caused by the friction of the tow guidance device and by the maximum stress which can be carried by the tow. For winding of glass fibers a minimum tow tension is recommended in order to introduce only low residual stresses in the rings. With an increasing compaction pressure a better matrix flow can be reached, which guarantees a lower void content between the fibers. But also the compaction pressure (consolidation force) has an optimum value (450N). Higher consolidation forces damage the fibers and cause squeezing of the molten polymer out of the rings' cross section.

For this special winding arrangement investigated a winding speed between 6 and 12 m/min leads to the best results. When realizing higher winding speeds, there is not enough time for the melting- and consolidation process; in addition, there is not enough time for heat exchange between the hot air and the incoming tow. In case of lower winding speeds, the tow material remains to long in the hot air region of the nip point, so that the matrix material may get degraded at its surface.

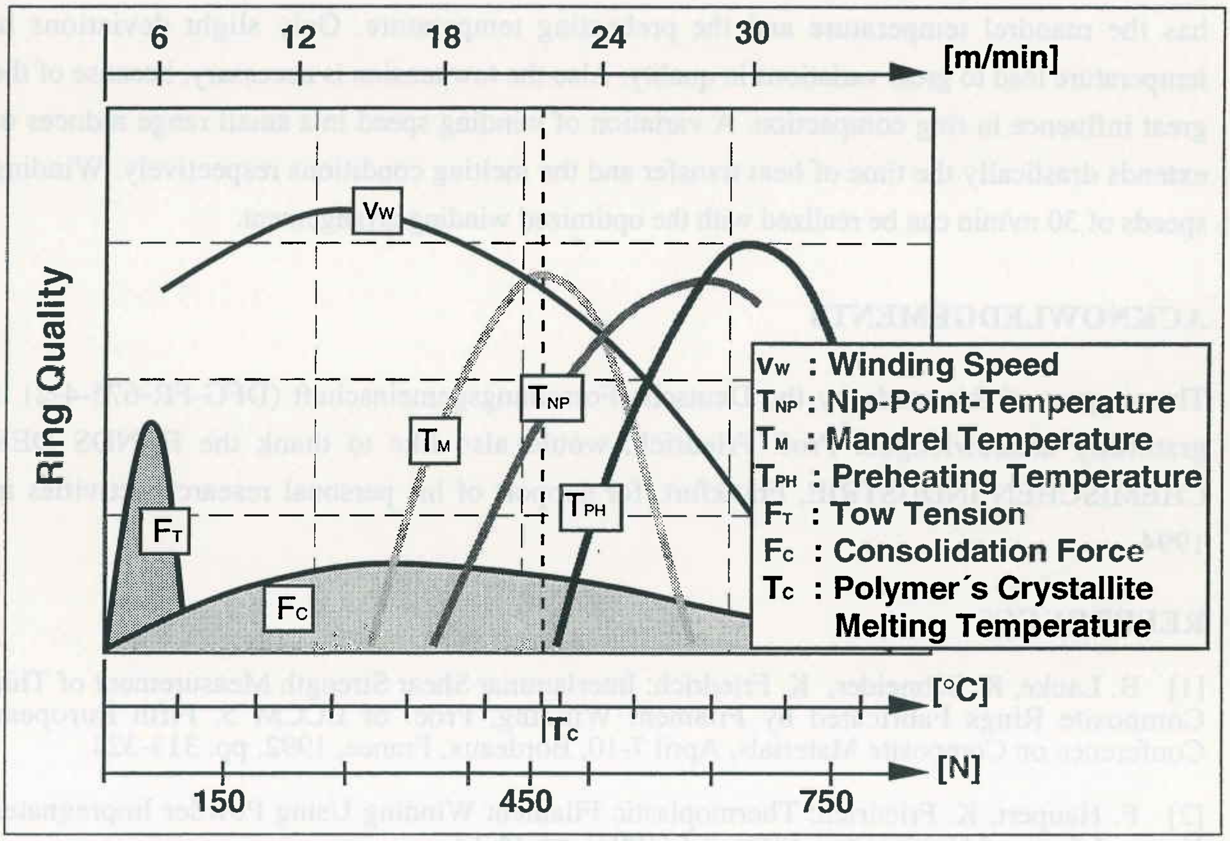

Figure 8: General trends of ring's quality as a function of winding parameters

The optimal processing parameters for the materials investigated in the In Situ Process are shown in Table 1 for GF-PET 1200tex.

Material	Tow Tension [N]	Consolidation Force [N]	Mandrel Temp. [°C]	Nip-Point-Temp. [°C]	Winding Speed [m/min]	Preheat. Temp. [°C]
GF-PET 1200tex	21	450	250	250	12	360

Table 1: Optimal processing window of the In-Situ Process

CONCLUSION

Meanwhile, the In-Situ-Consolidation Process (ICP) has reached such a high level of production quality in winding of simple geometries, that from now on it can be focused on the production of complex geometries. A great influence on the consolidation quality of the rings has the mandrel temperature and the preheating temperature. Only slight deviations in temperature lead to great variations in quality. Also the tow tension is necessary, because of the great influence in ring compaction. A variation of winding speed in a small range reduces or extends drastically the time of heat transfer and the melting conditions respectively. Winding speeds of 30 m/min can be realized with the optimized winding arrangement.

ACKNOWLEDGEMENTS

The support of this study by the Deutsche Forschungsgemeinschaft (DFG-FR-675-4-2) is gratefully acknowledged. Prof. Friedrich, would also like to thank the FONDS DER CHEMISCHEN INDUSTRIE, Frankfurt, for support of his personal research activities in 1994.

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