Thermoplastic Filament Winding - An Experimental Investigation of the On-line Consolidation of Polyetherimide-FIT Preforms

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ABSTRACT

The development of manufacturing techniques for thermoplastic composites toward an industrial scale requires new processing technologies. Regarding the filament winding process, the use of thermoplastic preforms has economical advantages compared to thermosets, if similar fibre placement speeds are achievable for similar costs of equipment and preforms, such as powder impregnated (FIT) or intermingled yarns.
The presented experimental work compares two different processing techniques based on a hot air heater and short wave infrared spot and discusses the influence of preheating the preforms and the mandrel. The investigations have been carried out on powder impregnated polyetherimide preforms (FIT), which are processed to hoop wound tube specimens. The characterisation of the laminate quality is based on micrographs. The results show the importance of continuous heating at low heating rate. Discontinuous temperature peeks above the matrix melting temperature lead to its thermal degradation and therefore to poor laminate quality.

1. INTRODUCTION

In recent years fibre-reinforced thermoplastics such as high performance composites have been considered increasingly as an alternative to traditional thermoset materials. This tendency is related to the promising advantages of these materials such as higher fracture toughness, low moisture absorption, long shelf life, recyclibility, and continuous processing by elimination of the curing stage that is characteristic of thermosets. Nevertheless the key aspect to introduce thermoplastic-matrix composites in industrial applications is the development of cost effective manufacturing processes. Up to now a general lack of such processing methods is the reason that thermoplastic composites have found only very few series applications /1/.
In previous works /2-4/, it has been demonstrated that in situ consolidation can be reached during thermoplastic filament winding. Therefore filament winding might be a suitable manufacturing technique for continuous fibre-reinforced thermoplastic components.
Among the manufacturing techniques for thermoset materials the filament winding offers the possibility of cost effective manufacturing, mainly due to its automation in fibre placement, its high production speed and its low material and labour costs. Today fibre speeds for wet

filament winding are limited to about 1-2 m per second /5/, which is given by the impregnation behaviour of dry fibres with resin.

It is obvious, that the use of fibre-reinforced thermoplastics in filament winding technology only offers economical advantages, if the following requirements for a manufacturing concept are taken into account:

- The winding technique should lead to a similar production speed as for thermoset processing without any loss of laminate properties.
- A new processing unit should allow similar costs for equipment and energy use as for thermosets.
- Thermoplastic preforms should permit similar material costs as for thermosets in processing engineering or advanced thermoplastic composites.

Consequently a better understanding of the fundamentals of processing technique including the associated mechanisms of heat and resin flow is needed to fulfil these conditions.

The primary object of the present work is to compare two different processing techniques based on a hot air heater and short wave infra-red spot and to demonstrate its feasibility for powder impregnated preforms (FIT) including carbon fibre and polyetherimide (PEI) matrix. Therefore an experimental set-up was developed and used on an typical four-axis filament winding machine.

2. FILAMENT WINDING TECHNIQUE

Thermoplastic preforms offer the possibility of bonding two prepregs by melting their surfaces while applying pressure. Therefore thermoplastic wounded composite parts are processed in a single production step. Melting, consolidation and cooling steps take place in a continuous process during the laydown of the thermoplastic prepreg onto the mandrel (Fig. 1). Before laydown occurs the running preform is heated to the process temperature of the thermoplastic matrix by applying continuous heat flow at low heating rates in a so called preheating chamber.

The temperature after the preheater should be slightly less than process temperature to avoid adhesion of molten matrix to any fibre delivery systems.

The temperature of the mandrel surface during processing should be as well as the temperature of the preheated composite material to avoid preliminary thermal degradation of the matrix. Therefore a heating system is used for the inside and outside heating of the mandrel.

The bonding between the incoming preform and the laminate is obtained by focusing a heat source, melting the matrix, and applying a pressure gradient normal to the mandrel surface at the contact point. The high density of energy allows further to increase quickly the viscosity in the welding point area, and the pressure gradient induces the resin flow. Further the laminate has to be maintained at constant temperature and pressure to be fully consolidated. Regarding the continuous of thermoplastic filament winding process, this last aspect is difficult to be fulfilled.

Nevertheless a pressure gradient normal to mandrel surface is achieved either by applying a consolidation roller or shoe at the contact point, or only by the tension of the preforms. The processing speed, which is important for cost effective manufacturing, and the dynamic of a consolidation roller or shoe is difficult to handle for complex mandrels, therefore it should not be used any roller if possible for the consolidation of the laminate.

3. EXPERIMENTAL

The bonding of the prepregs plies is achieved through a thermowelding process which could include induction, infra-red, ultrasonic, microwaves or contact heating.

A gain-cost analysis of potential energy sources shows that hot air and focused infrared are the most promising heating methods with regard to costs and technical efficiency /6/. Therefore both heating techniques have been investigated by processing hoop wound tube specimens.

3.1 Investigated Material

The thermoplastic filament winding experiments have been performed with with HT300[1] carbon fibre and PEI[2]-matrix FIT[3]-preforms. The FIT-preform is obtained by impregnation of the fibres with polyetherimide powder. An outside jacket extruded from the same thermoplastic material sticks powder and fibres together /7/. The fibre volume fraction varies between 57% and 60%. Polyetherimide is an advanced amorphous thermoplastic and offers excellent mechanical and thermal properties. But the high viscosity of the melt often leads to processing problems. The dynamic viscosity of polyetherimide varies between $\sim 10^4$ Pas and $\sim 10^3$ Pas for a temperature range from 330°C to 370°C (shear rate from $0.1\, s^{-1}$ to $300\, s^{-1}$) compared to wet filament winding thermoset resins, where the dynamic viscosity lays between ~1 Pas and ~10 Pas.

3.2 Experimental Set-up

Figure 2 shows the thermowelding set-up fixed on a standard four-axis computer-controlled filament winding machine. The four degrees of freedom are: the rotation of the mandrel (C), the translation of the carriage parallel to mandrel axis (Z), the translation of the crossfeed axis vertical to the mandrel axis (X) and the rotation of the delivery head around an axis (A), which is parallel to the crossfeed axis.

The set-up is designed either for a hot air blown or a short wave infra-red spot. It also allows the winding of hoop and helical patterns. The centre line of the heat source passes through the rotation axis of the delivery head. Therefore the heat source focuses vertically on the mandrel surface for any winding angles. The incoming preform is placed on the mandrel in the direction of winding angle by the rotation of the delivery system.

A pyrometer, which is cofocused with the heat source on the contact point, allows a non-contact temperature measurement.

The consolidation of the plies have been obtained without any consolidation roller only by tensioning the preform. The fibre tension is applied through a dancing arm controlled servo-break.

The outside diameter of mandrel is 40mm, the length of the tube specimens is 150 mm and the wall thickness is 1.4 mm, which corresponds to 12 plies.

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[1] Torayca™ is a HT-carbon fibre from Toray Industries Inc., Japan

[2] Ultem™1010 is an amorphous polymer market from GE Plastics, UK

[3] FIT: Fibres Impregnated Thermoplastic developed by Atochem, France

3.3 Thermal Welding with Hot Air Blown

Figure 3 shows a typical hot air blown with a nozzle arranged vertically to the contact point an without preheating. The used blown transports hot air at a temperature of max. 700°C with a airflow rate of 900 l per minute.

Figure 4 shows the set-up with integrated preheating chamber for the incoming tow and th mandrel surface. The heat flow is oriented to the contact point and is partially divided into th preheating station, where the polyetherimide matrix is heated up smoothly. An insulating jacket around the mandrel reduces its temperature loss at the surface.

3.4 Thermal Welding with Infra-Red Spot

Figure 5 shows the 750 W short wave infra-red spot heater with an elliptical reflector fo focusing the heat flow. The auxiliary shield is cute near the focal point. The focal poi coincides with the contact point. An integrated preheating has been achieved by guiding th running tow through the reflector shield and by insulating the mandrel.

4. DISCUSSION

The results of the on-line consolidation experiments are presented in figure 6 to 13. The out and inner surface have been characterised. Further the quality of the laminates, based o micrographs have been discussed. The processing parameters have been optimised for each experiment.

4.1 Results of the Hot Air Blown Experiment

The hot air blown allows to melt the thermoplastic matrix of the tow without preheating the tow and the mandrel. The nozzle produces a strong air flow, which leads to the formation of matrix drops on the outer surface of the tube specimen (Fig. 6). The metallic mandrel removes he energy from the inner surface, which leads to a poor surface quality (Fig. 7). The micrograp shows the formation of PEI-layers and voids inside the laminate (Fig. 12). The optimise processing parameters are: fibre tension 5 N per 1000 filaments, welding temperature 650° C fibre speed 0.02 m per second.

The results of preheating the incoming tow and the mandrel are shown in figure 8 and 9. Th outer and inner surfaces of the tube specimen and the consolidation of the laminate have bee clearly improved (Fig.13). The optimised processing parameters are: fibre tension 5 N per 100 filaments, welding temperature 650°C, fibre speed 0.05 m per second, temperature of th mandrel 150°C, air temperature at the end of the preheating chamber 450°C.

4.2 Results of the Infra-red Spot Experiment

The short wave infra-red spot heater in combination with preheating makes possible to increas the processing speed to 0.08 m per second. The outer and inner surfaces of the tube specime have been improved (Fig. 10 and Fig. 11). The laminate quality of the tube is very similar t that represented on the micrograph in figure 14. The optimised processing parameters are: fibr tension 5 N per 1000 filaments, welding temperature 960°C, fibre speed 0.08 m per second temperature of the mandrel 150°C.

5. CONCLUSIONS AND SUMMERY

Two different experiments for on-line welding during the thermoplastic filament winding process, carried out on a hot air blown and a short wave infra-red spot, are presented. No consolidation roller was used to consolidate the laminate. In the first experiment heat sources are tested without preheating the incoming tow and the mandrel. In the second experiment the selected sources are used in combination with preheating. The importance of the preheating chamber has been confirmed. The result of these basic investigations are:

- Without the preheating of the incoming tow and the mandrel, a sudden heat flow through the tow is required to melt the polyetherimide in the contact point. This leads to the thermal degradation of the polyetherimide matrix on the surface and thus to a poor laminate quality.
- The focused short wave infra-red spot heater in combination with preheating is more efficient than the hot air blown. This is caused by the better suitability of infra-red for interply heating than hot air. Infra-red radiation is transmitted through laminate and consequently heats this below the laminate surface.

These thermoplastic filament winding experiments show also that more basic investigations are needed to optimise the process parameters fibre tension, heating power, preheating and welding temperature with the aim to increase the processing speed.
The experimental set-up described in this paper has been used for manufacturing small component like a hoop wound shroud for a compressor rotor, which is presented in figure 14.

6. REFERENCES

/1/ J. Brandt, K. Drechsler, H. Richter, ICCM-9, 6, 143, 1993

/2/ H. S. Kliger, B. A. Wilson, Composite Materials Technology: Processes and Properties / P. K. Mallick, S. Newman (Eds.). Hanser Publishers Munich Vienna New York; Oxford University Press New York, 6, p. 179, 1990.

/3/ B.Lauke, K. Friedrich, Composites Manufacturing, Vol. 4, 2, p. 93, 1993

/4/ B.T. Åström, R.B. Pipes, Fifth Technical Conference of the American Society for Composites, p. 219, 1990

/5/ E. Beyler, W.Phillips, S.I. Güçeri, Journal of Thermoplastic Composite Materials, Vol.1, p.107, 1988

/6/ J.Whiting, 3rd International Conference on Automated Composites (ICAC), 27, 1991

/7/ Atochem, Thermoplastics Polymers in Powders for Composites, Technical Report, Paris 1985

7. ACKNOWLEDGEMENT

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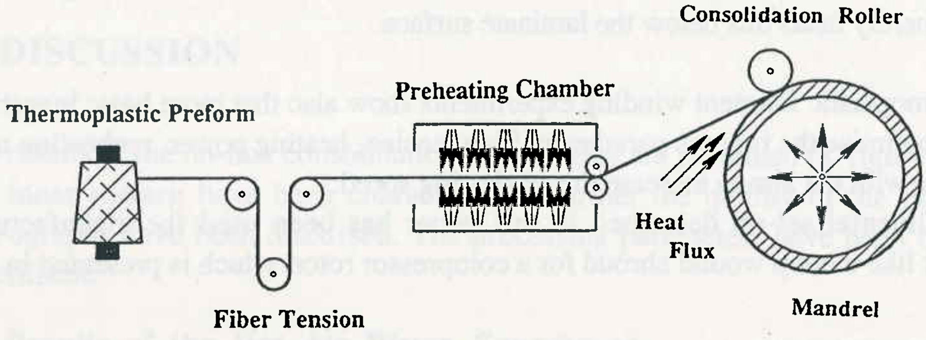

Fig. 1: Thermoplastic filament winding. Schematic layout of the thermowelding process.

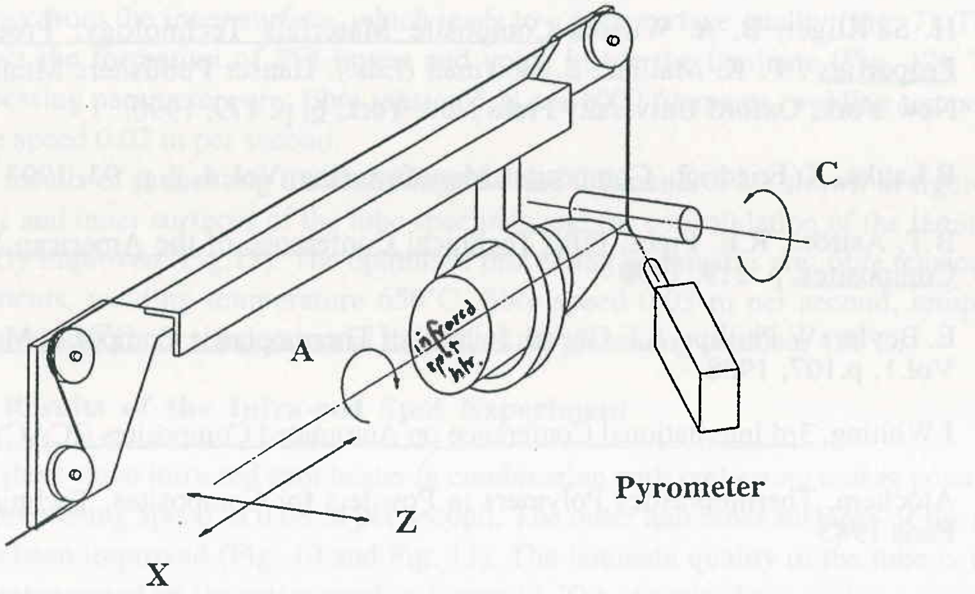

Fig. 2: Principal machine axes with heat source and pyrometer location.

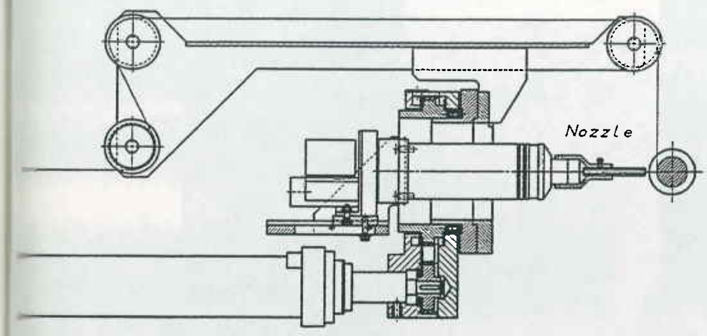

Fig. 3: Set-up with hot air blown and fibre delivery system. The blown transports hot air at a temperature of max. 700°C with an airflow rate of 900 l per minute.

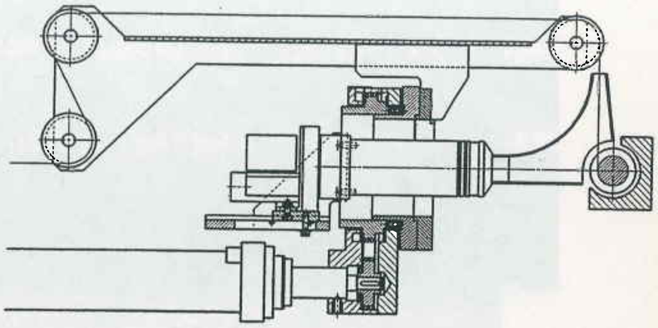

Fig. 4: Set-up with hot air blown and integrated preheating chambers.

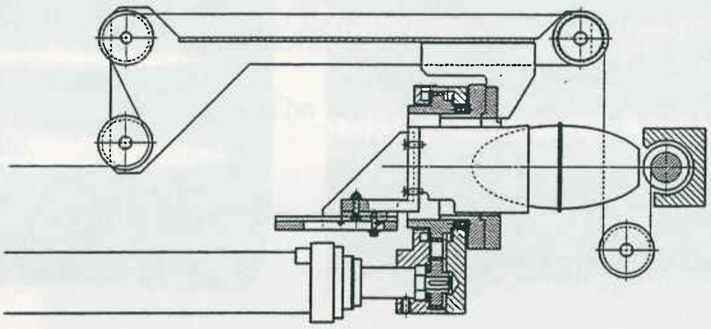

Fig. 5: Set-up with short wave infra-red spot and integrated preheating chambers. The focal point of the reflector coincides with the contact point of the incoming tow.

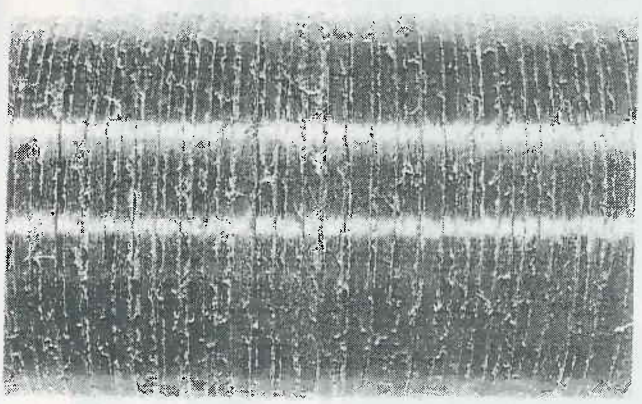

Fig. 6: Outer surface of tube specimen. Hot air blown without preheating.

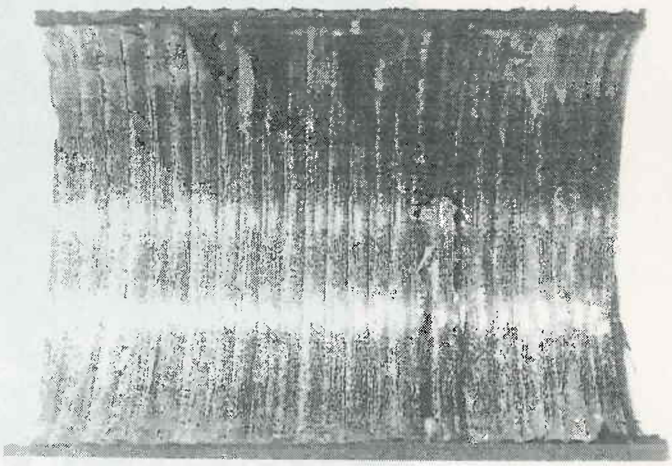

Fig. 7: Inner surface. Hot air blown without preheating.

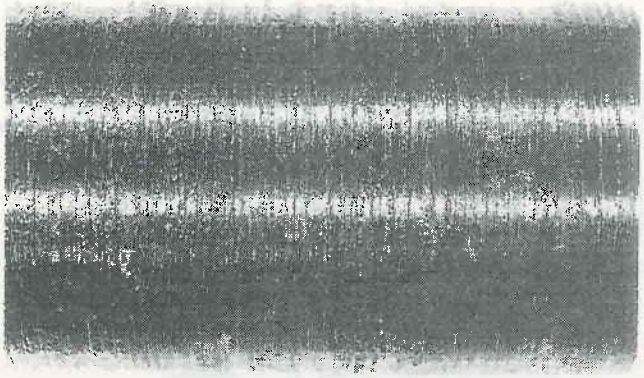

Fig. 8: Outer surface of tube specimen. Hot air blown with preheating the incoming tow and mandrel.

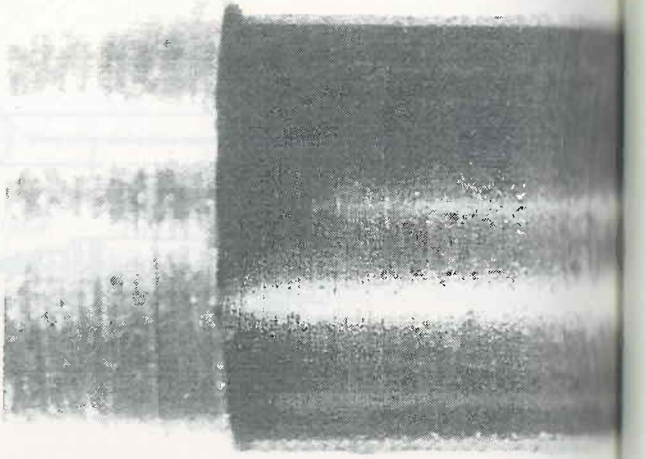

Fig. 9: Inner surface. Hot air blown with preheating.

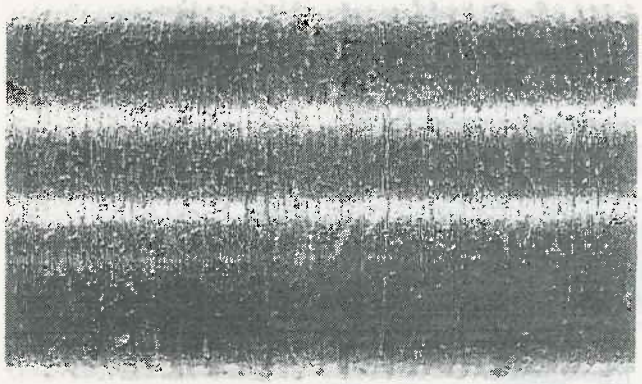

Fig. 10: Outer surface of tube specimen. Short wave infra-red spot with preheating.

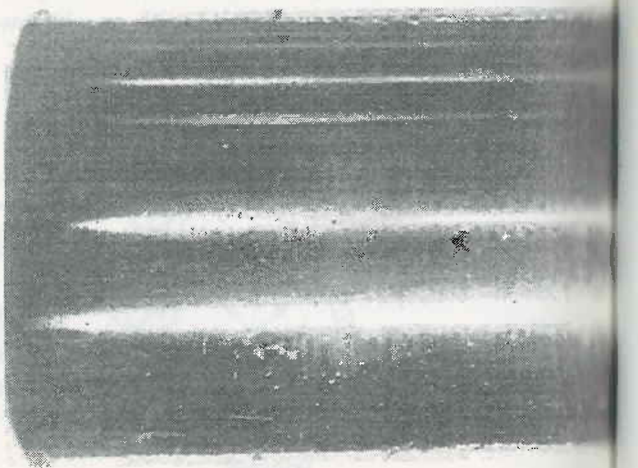

Fig. 11: Inner surface. Infra-red spot with preheating.

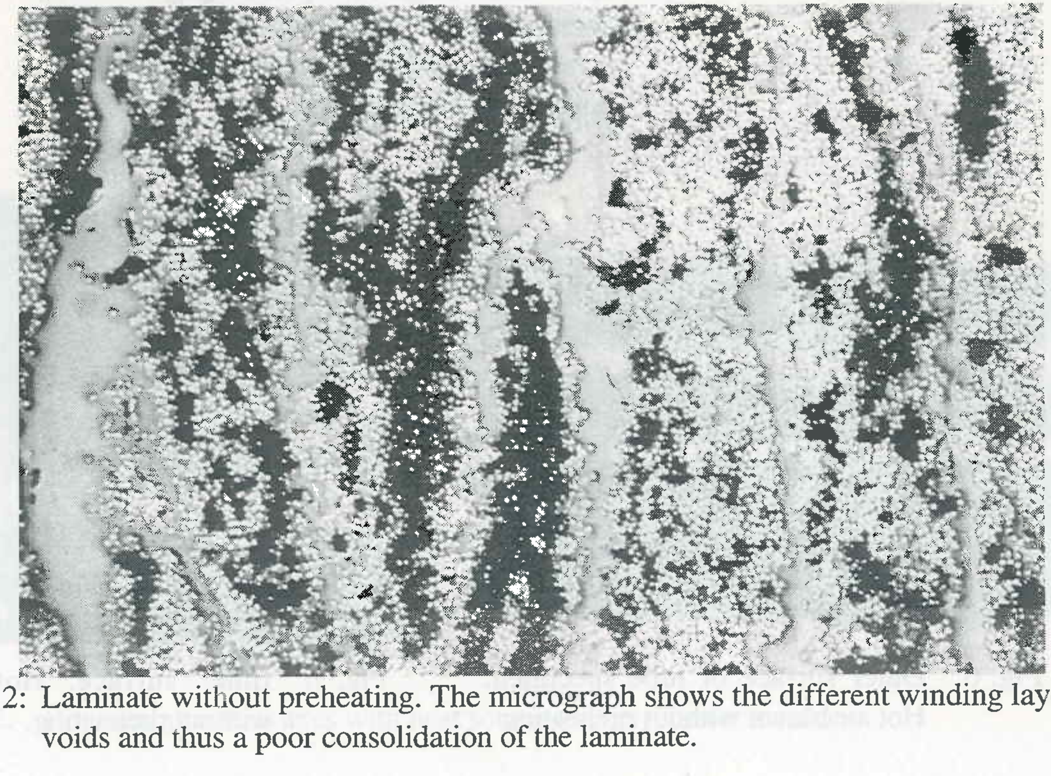

Fig. 12: Laminate without preheating. The micrograph shows the different winding layers and voids and thus a poor consolidation of the laminate.

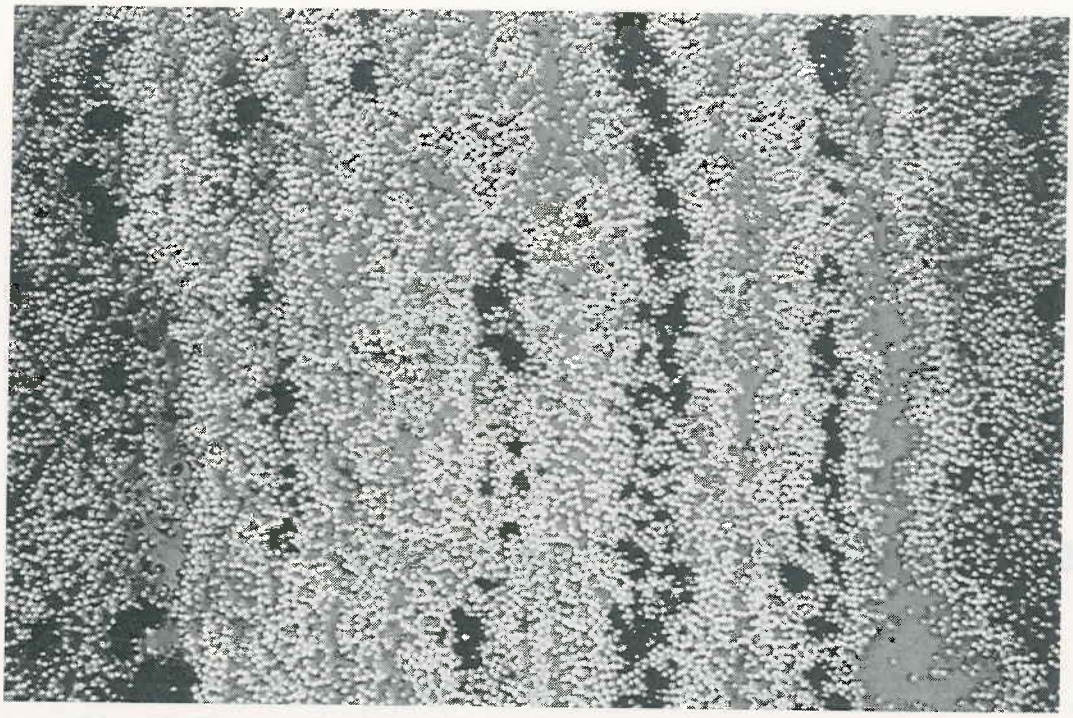

Fig. 13: Laminate with preheating. The micrograph presents a better consolidation of the composite.

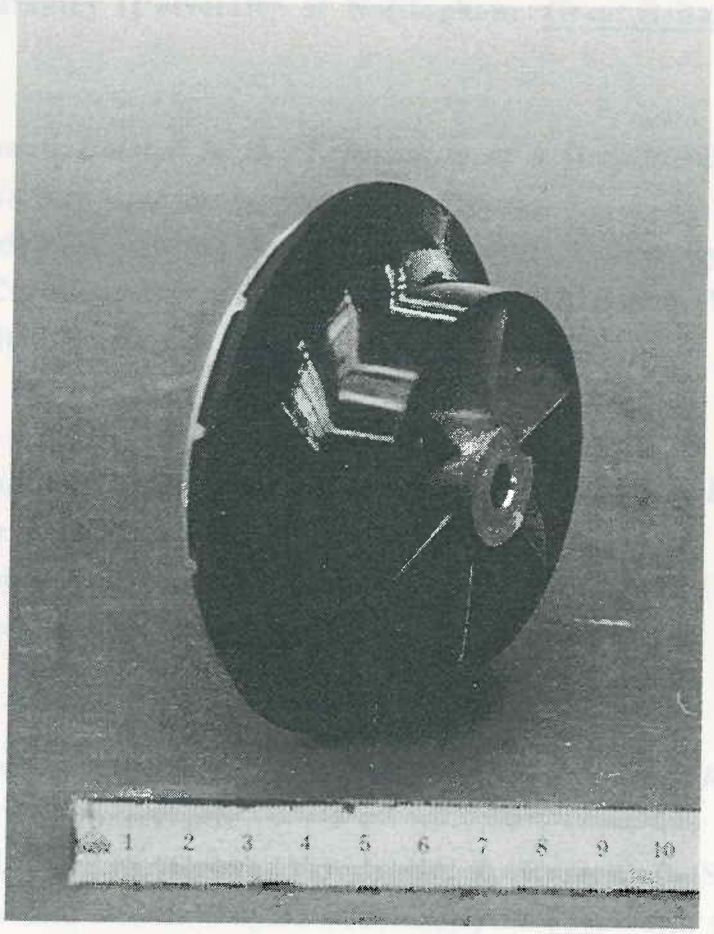

Fig. 14: Compressor rotor with a shroud (rotor diameter: 90 mm). The hoop wound shroud has been processed from polyetherimide FIT-preforms.