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T-technology: Close out report

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T-technology: Close out report

by

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Summary

This report provides an overview and summary of the Gas and Power sponsored T-technology R&D work carried out by Shell Global Solutions Upstream Materials, Corrosion & Inspection in the period 2007 – 2009.

The work was focussed on the application of a new single component composite material called all-polypropylene composite or “all-PP”. The composite material is based on pre-stretched polypropylene tapes. A large screening test programme has demonstrated that this material shows unique physical and mechanical properties under cryogenic conditions and that, with a suitable design, applications for cryogenic fluid barriers and pipes are believed to be feasible.

At the moment, the technology is at a proof of concept stage and more detailed design and testing would be required to enable the conceptual design of a prototype. The T-technology concept and the results of the cryogenic test programme formed the basis for a technology workshop with DNV that on 26 June 2009 resulted in a DNV certified “Statement of feasibility for the T-tank technology”.

Adhesive bonding of the all-PP material and its permeation behaviour under cyclic cryogenic conditions are seen as the main challenges to solve. However, based on the current results, all-PP is still seen as a promising alternative to 9%-Ni steel in a number of applications.

Amsterdam, February 2010

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1. Introduction

The T-technology R&D development is part of the Gas and Power sponsored R&D theme: “LNG Supply”. The T-technology is aimed at the replacement of expensive Ni-based steels for cryogenic applications with less expensive and easier to construct polymer based materials or composites.

Initially at the start of the project, a polyurethane based system was proposed as a potential material for the membrane in a LNG storage tank but this material did not perform satisfactory under cryogenic conditions. On cooling down this material, the thermal shrinkage exceeded the critical stress of the material, which resulted in cracking. An alternative material was identified, polypropylene single polymer composite, also indicated as all-PP. Although this material was already used for low temperature applications down to -40 °C because of its excellent impact resistance, its potential for cryogenic applications was not recognized by the manufacturers.

The pre-stretching step in the fabrication process is the key property which makes this material suitable for low temperature applications. It should be noted that other polymer materials like polyethylene are expected to show the same behaviour when pre-stretched in a similar manner.

Initial screening tests under cryogenic conditions revealed that all-PP material performed very well and could be considered as an alternative material to Ni-based steels. It was decided to further explore the feasibility of this material for cryogenic conditions.

Earlier studies [Ref. 3] already revealed that closed foam PVC was a potential insulation material for cryogenic conditions. The combination of the all-PP membrane material and the PVC-insulation material was identified as a potential solution to design a non-metallic based membrane for a LNG storage tank or for the design of a cryogenic pipe. This technology was indicated as T-technology. The feasibility of this technology concept from a materials design point of view was worked out in more detail in [Refs. 4 and 5] and formed the basis of an extended test programme to test the feasibility of the polymer materials under cryogenic conditions. Based on these studies, a number of patents were filed in which the application of this type of polymer materials for cryogenic service is protected [Refs. 6 and 7].

The T-technology concept [Refs. 5 and 8] and the results of the cryogenic test programme formed the basis for a technology workshop with DNV that on 26 of June 2009 resulted in a DNV certified “Statement of feasibility for the T-Tank Technology” [Refs. 1 and 2].

The test programme as defined in [Ref. 5] and carried out in 2008 and 2009, resulted in a number of tasks, which were focussed on the determination of the materials properties under cryogenic conditions. However, other items such as optimisation of polymer tapes used for the fabrication of single polymer composites, the jointing and QA/QC of the non-metallic components and feasibility of inspection were all considered to be key technologies required for a successful field application and had to be addressed in the studies. The roles, strength and weaknesses of potential partners needed to accomplish these tasks were analysed and the best partners were selected [Ref. 9].

This report collates the studies and summarizes the main findings and provides recommendations for possible follow up work.

2. Overview of the studies

The following list gives an overview of the activities and partners involved.

- **Task 1: Characterisation of the polymer materials**
  Testing of mechanical and physical properties of PVC insulation foam and single polymer composites under cryogenic conditions. These tests were carried out by both Shell Global Solutions, DIAB the supplier of the PVC foam and a number of external test houses.

The test material used for the composite was the standard grade single polymer material in sheet form and was supplied by Propex Germany. The commercial name of this material is 'CURV'. The objective of Task 1 was to characterise the commercial available CURV material.

- **Task 2: Optimisation of the all-PP tapes for cryogenic conditions**
  Queen Mary University was involved during the initial developments of all-PP composites and worked together with Lankhorst in the Netherlands to develop pre-stretched polypropylene tapes. The brand name of this material is PURE and Lankhorst is the patent holder. Nano-force, in liaison with Queen Mary University in London, carried out a test programme to look at the optimum draw ratio of the single polymer composite. This work was carried out on single tape bundles. Propex Germany, a supplier of single polymer composite sheet material, was asked to manufacture different plates made of tapes with different draw ratios. These materials were used to carry out the permeation and fatigue tests as described in Task 3. The main objectives of Task 2 were to identify the critical parameters needed to optimise the commercial available tapes for cryogenic applications.
- **Task 3: Permeation testing and fatigue testing of the single polymer composite material under cryogenic conditions.**
  These experiments required special expertise and unique equipment. The "Institut für Luft- und Raumfahrt - Lehrstuhl für Leichtbau", a faculty of the technical university of Munich (TUM), had developed a worldwide unique permeation test facility to be able to carry out permeation tests under cryogenic conditions. A screening test programme was carried out to test the permeation of the single polymer composite material as function of the draw ratio of the tapes used in the composites. TUM also carried out a fatigue screening test programme on PP single-polymer composite material.
- **Task 4: Adhesive bonding of non-metallic components**.
  The tasks comprised of:
  - Identification of suitable pre-treatment methods for the non-metallic components;
  - Identification of a suitable adhesive for the application under cryogenic conditions;
  - QA/QC of adhesive bonding, including suitable inspection techniques.

  Acceptance criteria were defined and Sergem Engineering in the Netherlands, who specialize in adhesive bonding techniques, was asked to carry out this study.
- **Task 5: Design, manufacturing and proof of concept testing of a polymer based cryogenic pipe**.
  The objective of this task was to demonstrate that the manufacturing of a cryogenic pipe based on all-PP tapes is possible ("proof of concept testing"). A number of pipes were manufactured by Airborne Composites based in the Netherlands. The raw materials used were pre-stretched tapes supplied by Propex Germany. The internal liner with an aluminium barrier was supplied by Egeplast Germany. The end-fittings for the pressure tests were designed by Airborne. A cyclic cryogenic test was carried out by Airborne and witnessed by Shell Global Solutions. Note that this test was a cyclic temperature test at atmospheric pressure conditions.

2.1 Task 1: Characterisation of the polymer materials

For the conceptual design of the membrane tank and cryogenic pipe, two materials were selected: the all-PP CURV material as a membrane for the LNG containment and PVC foam as a closed cell insulation material. The All-PP CURV material was supplied by Propex in Germany and it is a standard grade. The PVC insulation material was supplied by DIAB in Sweden and is a standard Divinycell H60 and H80 material. A test programme was defined and carried out as described in [Ref. 5]. The datasheets and test results of the experiments are reported in Appendices A to E.

The highlights of the test programme were:

- The key mechanical and physical properties of both PVC insulation foam and all-PP composite material were measured and reported;
- The all-PP composite material maintains a ductile behaviour under cryogenic conditions and shows a high potential for the application under cryogenic conditions;
- The fracture toughness of the material under cryogenic conditions is high. Because of its ductility, measurement of the plane strain fracture toughness under linear elastic fracture mechanics (LEFM) is not possible, and only a thickness dependent plane stress fracture toughness could be determined. To determine a thickness independent fracture toughness value, elastic plastic fracture mechanics (EPFM) tests would be required. However, because of the practical implications of testing under cryogenic conditions, instrumented testing required for EPFM is challenging;
- Because of the high ductility but relatively low strength of the all-PP composite material under cryogenic conditions, the design of e.g. a membrane tank will require a strain based design instead of a stress based design;
- The commercial available material could probably be further optimised for cryogenic conditions (see Task 2);
- Pores were observed in the commercial available CURV material. The effect on the permeation of LNG needs to be further evaluated (see Task 3).

2.2 Task 2: Optimisation of the all-PP tapes for cryogenic conditions

Nanoforce was asked to determine the critical parameters required to further optimize the all-PP composite material. From earlier studies carried out by Nanoforce, it was found that both the pre-stretch level of the tapes component also the interface between tape and matrix are the most important parameters which will determine the mechanical properties of the composite. Pre-stretching results in suppression of the glass transition temperature that will give the polypropylene tapes their unique ductility at low temperature. The pre-stretching is expressed as the draw ratio that is the ratio between the stretched tape and the unstretched tape. Typically, the draw ratio is in the order of 8 – 15.

There are currently two different suppliers on the market, Propex and Lankhorst. The difference between the products is the way the tapes are manufactured. Propex uses a single polymer for the manufacturing of their tapes and the plate material is manufactured by pressing layers of wovings made of pre-stretched polypropylene tapes together with polypropylene foils under high pressure and temperature to melt the components together. Parts of the tapes will melt, which will have an effect on the performance of the end product. The temperature will result in a loss of draw ratio due to relaxation of the pre-stretched tapes, especially at the tape/tape interface and the tape/foil interface.

Lankhorst on the other hand, produces co-extruded tapes. In this way, the pre-stretched tapes are covered by a thin layer of a co-polymer with a lower melting point. During the manufacturing of the composite plate material, lower temperatures are required to melt the tapes together. As a result the relaxation will be less and the reduction in draw-ratio will push the glass transition temperature back to a higher level, thus affecting the low temperature performance of the material.

The objective of the study carried out by Nanoforce was to explore/screen the effect of draw ratio focussed on;

- Finding the optimum draw-ratio of co-extruded tape. This was accomplished by testing tapes produced at different draw ratios and quenching temperatures and testing these tapes under cryogenic conditions;
- Identifying possible alternative low melting co-polymers for the co-extruded skin layer of the tapes to reduce tape relaxation and enable low temperature jointing techniques (thermo-welding).

The results of the studies are attached as Appendices F and G. The highlights of the studies were:

- The optimum draw ratio of the tape that produces the highest strain at failure (12.5 %) under cryogenic conditions is six;
- The effect of quenching temperatures (room temperature and 95 °C) was found to have no significant effect on the crystallinity and strain at failure under cryogenic conditions;
- As explained above, the effective remaining draw ratio, as a result of the applied temperature during manufacturing, will be reduced. In the design of the composite, this has to be accounted for. Note that for the CURV material made by Propex, typically tapes with a draw ratio of about twelve have been used. The final effective draw ratio after manufacturing might be as low as six but is unknown;
- Screening peel tests to measure the bonding between the tapes and the co-polymer skin material indicated that the performance of low melting polypropylene co-ethylene polymers may be a good alternative as a tape skin material. Especially the DOW Versify 2300 showed very promising peel forces. The use of these polymers would enable the application of lower manufacturing temperatures and thus will limit the stress relaxation of the pre-stretched tapes. These low melting temperatures also enable the use of steam for consolidation of the tapes;
- The studies carried out by Nanoforce were set up as a first screening to explore the effect of draw ratio, crystallinity and type of co-polymer for the co-extrusion grade. A more in-depth investigation would be required to explore the overall effects on other properties such as manufacturing, permeation, creep, fatigue etc.

2.3 Task 3: Permeation and fatigue testing

Permeation under cryogenic loading conditions is an important design criterion for a LNG storage tank membrane. During the mechanical tensile tests, it was observed that small “pop-in” type of events occurred during the tensile loading of the all-PP plate material. It is believed that these events are related to debonding or crack events at a micro scale. This, however, could not be confirmed.

The aeronautic department of the Technical University in Munich (TUM) has developed unique equipment for in situ loading - permeation testing of plate material as well as for the fatigue testing of polymer components under cryogenic conditions.

The objectives of the studies carried out by the University of Munich were:

- Screening test to explore whether it is possible to use the TUM permeation test rig for the measurement of permeation through an all-PP plate material. Helium was used as permeant. With the TUM test rig, it is possible to carry out an in-situ permeation test as a function of the mechanical load of the test specimen. The tests were carried out under liquid nitrogen conditions, and using helium as a permeant.
- Carry out fatigue experiments on all-PP materials with the standard draw ratio of twelve. The number of cycles was selected at 600 cycles, which is representative for the number of loadings/unloadings a LNG storage tank will see during its total lifetime. The level of relaxation after manufacturing is unknown.

The specimens were manufactured and supplied by Propex in Germany. Both translucent tapes, without carbon black as a filler, and black tapes, with carbon black as a filler, were used for the manufacturing of the all-PP composite plate. In the TUM report, these are indicated by the codes “B” and “T”. The fatigue experiments were carried out at both -150 °C (lowest possible temperature of the fatigue test rig) and –120 °C (temperature of the LNG liquid/gas transition region in a storage tank). The fatigue experiments were carried out at three different strain levels: 0.93 %, 1.39 % and 1.85 %. These represents the strains at -165 °C at a level of resp. 25 %, 50 % and 75 % of the tensile strength at yield.

- TUM also has a leading role in the development of tape optics in composite materials. It was asked to provide an overview of this technique as it is seen as a possible application for monitoring the condition of membranes.

The results of the TUM studies are provided in Appendix H. The main findings of the studies were:

- Both the translucent and black version of the all-PP CURV material did not reveal any visual damage after 600 cycles tested at -150 °C and -120 °C;
- During the fatigue experiments, the E-modulus was found to change with the number of cycles. Depending on the strain level of the E-modulus, changes observed were between +4.3 % and -10.9 % for the translucent material and between -0.5 % and -11.8 % for the black material.
- The Poisson ratio showed an unexpected low value at cryogenic conditions. It is unknown whether this was a test artefact or a material behaviour. It would require further research to explain this behaviour.
- The helium permeation experiments under liquid nitrogen conditions revealed that the adhesive bond between the membrane and the aluminium seat of the measurement cell is critical. In spite of the efforts to find a suitable cryogenic resistant adhesive, all experiments showed leakage via the adhesive bond. This means that no permeation could be measured as function of the mechanical load. However, at low strains it was demonstrated that the helium permeation under liquid nitrogen temperatures (-196 °C) was as low as $3.8.10^{-9}$ mbar.l/s. This is a very low permeation and a promising result. More research will be required to investigate the effect of the mechanical loading. The identification of a suitable cryogenic resistant adhesive for polypropylene is crucial to carry out successful permeation measurements.

2.4 Task 4: Adhesive bonding selection and QA/QC of field joints

Sergem Engineering in the Netherlands was asked to carry out a study on the selection of the pre-treating and adhesive bonding for jointing similar and dissimilar polymer materials.

The joining of the following material combinations were addressed in these studies:

– All-PP to All-PP;
– HDPE to HDPE;
– All-PP to PVC insulation foam;
– HDPE to PVC insulation foam;
– PVC insulation foam to Concrete;
– All-PP composite to Aluminium foil;
– HDPE to aluminium foil;
– PVC insulation foam to aluminium;
– Melamine foam (Basotect) to All-PP;
– Melamine foam to HDPE.

The subtasks defined were as follows:

- Identify and select a proper pre-treating method for the preparation of the bonding area;
- Identify adhesives for the application under cryogenic conditions;
- Carry out the specimen design and identify a company to manufacture the test specimens for the testing of the pre-treatment and adhesive bonding specimens;
- As a professional adhesive specialist, develop a philosophy how to apply QA/QC on adhesive bonding in the field.

Selection criteria were defined which also focussed on ease of application in the field, feasibility of automisation, total bonding time etc. The results of these studies are provided in Appendices I, J and K.

The main findings of the adhesive bonding studies were:

- Candidate pre-treatments and applicators were identified for the polymers and for the concrete, foams and aluminium foil. Potential candidates for the cryogenic adhesives were approached and the best available adhesives were selected. Full details on the pre-treatments, adhesive suppliers and selected adhesives can be found in Appendix I;
- For the performance testing of the adhesive bonding specimens, double lap-shear and single lap shear test were designed by Sergem. The specimens were manufactured by IKTZ in Germany. Appendix J provides a full report with the details;
- The QA/QC aspects for adhesive joint systems are described in Appendix K. This report describes the adhesive bonding procedure aspects, quality measurement and analysis, QA/QC philosophy for the LNG tank membrane, certification of bonders etc. Also some alternative inspection methods are described for the testing of leak tightness of the adhesive joints. Among these are the vacuum-box test, the US pulse echo method and the acoustical Fokker Bond Testing.

It was the intention to test the manufactured pre-treatment/adhesive bonding combinations in 2009, but a management decision was taken to skip this part from the current programme.

2.5 Task 5: A cryogenic pipe for proof of concept testing

Airborne Composites was asked to design, manufacture and pressure test a composite pipe for cryogenic applications. This task was seen as a proof of concept of the application of the all-PP material as a membrane material for cryogenic applications. The results of the pressure test on the single polymer composite tube can be found in Appendix L. The main findings of this task were:

- Airborne has demonstrated that it is possible to manufacture a tube from the standard commercial available PP tapes from Propex;
- It was demonstrated that the manufactured all-PP cryogenic tube could withstand, at least, six liquid nitrogen refills at atmospheric pressure over a period of four days. The pipe has seen, at least, seven hours below -165 °C. During this test, no leakage was observed. After the refill cycles, the test was stopped and visual inspection revealed no cracks or visual damage;
- After the cyclic cryogenic refill test, the pipe was subjected to an atmospheric leak test and revealed no leakage.

3. References

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2. DNV, "SOF2009-0976 Det Norske Veritas - Statement of Feasibility T-tank technology", SOF2009-0976, DNV, 2009
3. F.A.H. Janssen, "Characterisation of rigid PVC-foam Divinycell H grade for LNG full containment tank bottom insulation", OP.97.20245, Shell 1997
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6. F.A.H. Janssen and L.M. de Mul, *Patent TS 8670 - Use of a composite material as a barrier under cryogenic conditions*. 2009.
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8. S. Colwell and L.M. de Mul, "Qualification Basis - T-technology", GS.08.52829, Shell Global Solutions, 2009
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Appendix A. Datasheet of CURV all-PP composite material

Appendix A - CURV
datasheet Propex.pd

Appendix B. Datasheet DIAB PVC Insulation foam

Appendix B -
Datasheet DIAB PVC

Appendix C. Characterisation of CURV all-PP polymer sheet

C.1 Characterisation of Curv sheet and comparison with other common polymers

C.1.1 Density

The density of Curv and other possible candidate materials (PC, PTFE, PP, HDPE) was determined according to ISO 1183-1 (method A) using isopropanol as immersion liquid. The results are listed in Table C-1.

Table C-1 *Density of Curv and four other polymers*

Polymers	Density g/cm^3
Curv 3mm	0.924
Curv 1mm	0.927
PC	1.195
PTFE	2.170
PP	0.910
HDPE	0.934

C.1.2 Charpy impact tests

Charpy impact tests were performed according to ISO 179-1. Due to the available sheet thickness, specimen sizes were modified to 80x10x3 mm for Curv and to 80x10x4 mm for PC, PP, PTFE and HDPE. Specimens were notched at one face with notch type A. The impact tests were performed at room temperature (23 °C) and at cryogenic temperature. Therefore specimens were submerged in liquid nitrogen (-193 °C) for a period of 15 minutes, removed, placed in the testing machine and tested at RT. The time between removal from nitrogen and the impact test was measured and the temperature was corrected for that heating time by means of a calibration curve for the appropriate material.

The most suitable pendulum size for each type of material was determined by preliminary tests. The results of the impact tests are listed in Table C-2 and shown as bargraph diagram in Figure C-1.

Table C-2 *Charpy impact resistance of Curv sheet and four other polymers*

Polymer material	Pendulum size, J	Average Charpy impact resistance of 10 measurements				
		RT: 23 °C		Cryogenic temperature,		
		mJ/mm^2	STDV	mJ/mm^2	STDV	Calibrated temperature, °C
Curv 0°	7.5	111.6	9.6	132.8	21.5	-161
Curv 45°	7.5	171.7	8.9	111.1	9.3	-161
Curv 90°	7.5	103.1	6.9	120.1	12.7	-163
PC	0.5	6.1	1.6	2.9	0.2	-167
PTFE	0.5	9.9	0.3	5.7	0.7	-177
PP	0.5	3.5	0.5	2.3	0.2	-175
HDPE	2.0	*	*	10.7	0.7	-175

* Specimens slipped through the bearing, did not break

C.1.3 Thermal analysis

Melting point

Thermal analysis had been performed to determine the thermal properties of Curv sheet. The melting point was measured by Differential Scanning Calorimetry (DSC) according to ISO 11357-3, with a heating rate of 20 °C/min to be 162 °C (Figure C-2). A glass-transition (T_g) could not be detected with this technique[1].

Specific heat capacity

Specific heat capacity was determined by DSC according to ISO 11357-4, using sapphire as reference material. The measures specific heat values are listed in Table C-3 and the DSC scan is shown in Figure C-3.

Table C-3 *Specific heat capacity of Curv as measured by DSC*

Temperature °C	**Specific heat capacity, J/g*K**
-110	0.4
-100	0.6
-90	0.7
-80	0.7
-70	0.7
-60	0.7
-50	0.8
-40	0.8
-30	0.8
-20	0.9
-10	0.9
0	1.0
10	1.0
20	1.1
30	1.1
40	1.2
50	1.3

Glass-transition

Dynamic Mechanical Analysis (DMA), performed according ASTM E1640-04 in the single cantilever mode, showed a T_g at approximately -10 °C (onset[2] of the drop of the storage modulus in Figure C-4). Heating rate during the DMA scan was 2 °C/min. and the loading frequency was 1 Hz.

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1 PP is a semi-crystalline thermoplastic polymer with about 70-80 % crystalline molecules and an amorphous part of 20-30 %. It therefore shows no clear glass-transition in the DSC scan. Especially the PP fibres of the Curv material are highly crystalline with only a very small part of amorphous molecules.

2 Alternatively a glass transition can be determine by measuring the peak of the loss modulus (T_l = 7 °C) or the peak of the tangens delta curve (T_t = 11 °C).

Coefficient of linear thermal expansion (α)

The coefficient of thermal expansion was determined according to ISO 11359-2 by thermal mechanical analysis (TMA). A change in the slope of the thermal expansion curves (Figure C-5) indicates the glass transition and therefore is thermal expansion coefficient usually lower below than above the T_g. Both values are measured listed in Table C-4.

Table C-4 *Coefficient of thermal expansion of Curv as measured by TMA*

Linear thermal expansion	**α, *e-6/ °C thickness direction***	**α, *e-6/ °C in fibre direction***
below T_g (between –60 and –20 °C)	52 ± 7	26 ± 4
In the T_g area (between 0 and 20 °C	79 ± 20	44 ± 7
above T_g (between 40 and 70 °C)	125 ± 33	120 ± 61

* average of three measurements

Thermal conductivity

Thermal conductivity was determined according to ISO 8302/ASTM C177 at several temperatures. The results are listed in Table C-5.

Table C-5 *Thermal conductivity of Curv*

Temperature °C	**Thermal conductivity, W/mK**
-170	0.13
-120	0.13
-80	0.14
-40	0.14
-20	0.15
-40	0.15

C.1.4 Microscopical characterization of Curv

Curv sheet material is a composition of several layers of woven fabric, which have been sealed in a rolling mill to 1 or 3 mm thick sheet. Figures C-6 shows the surface of 3 mm thick sheet.

Incident Light Microscopy (LM)

A sample of the Curv material was cut, embedded into resin, and prepared for incident light microcopy examination. Figure C-6 shows the typical microstructure of 3 mm sheet cross-section. PP fibres are imbedded in a matrix of PP.

Scanning Electron Microscopy (SEM)

Cross-section of unconsolidated Curv fabric was examined by means of SEM (Figure C-8). The fabric is woven of particular strands that are composed of many very thin fibres. The diameter of the smallest fibres is far smaller than 1µm.

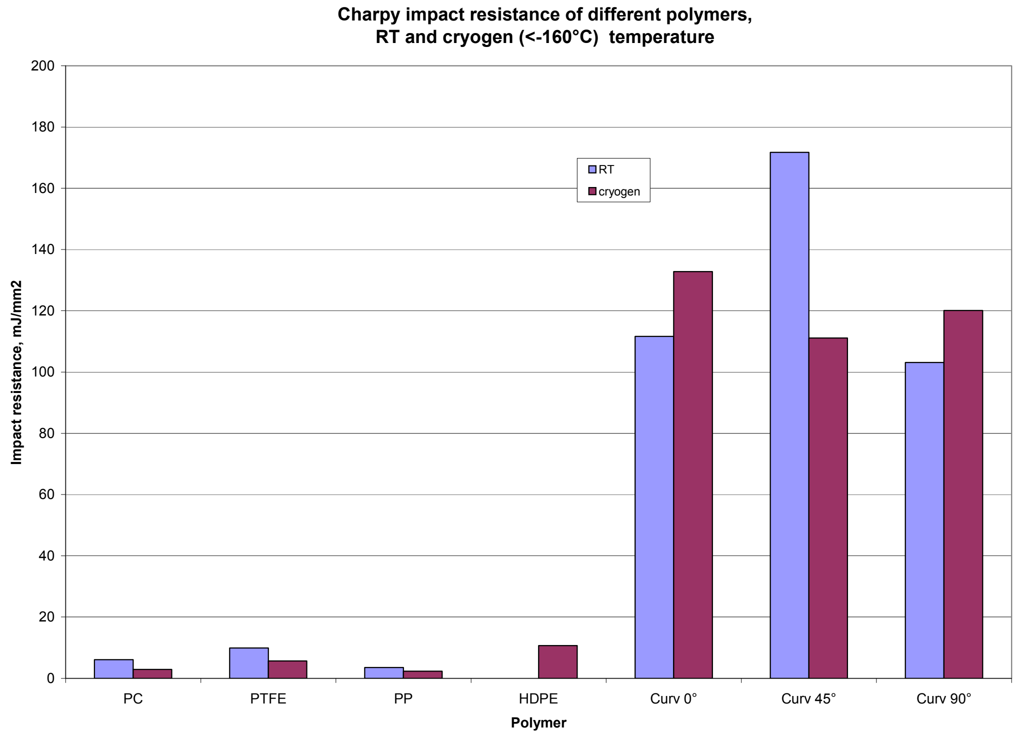


Figure C-1 *Summary of the Charpy impact tests*

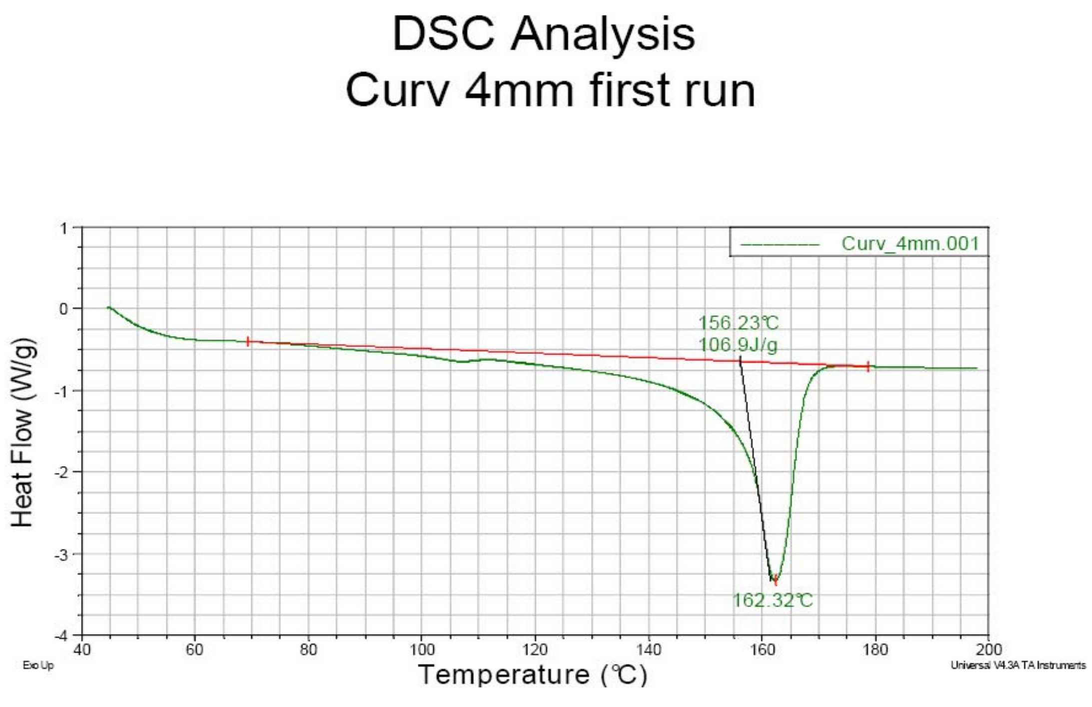


Figure C-2 *DSC scan of Curv material showing a melting point at 162 °C*

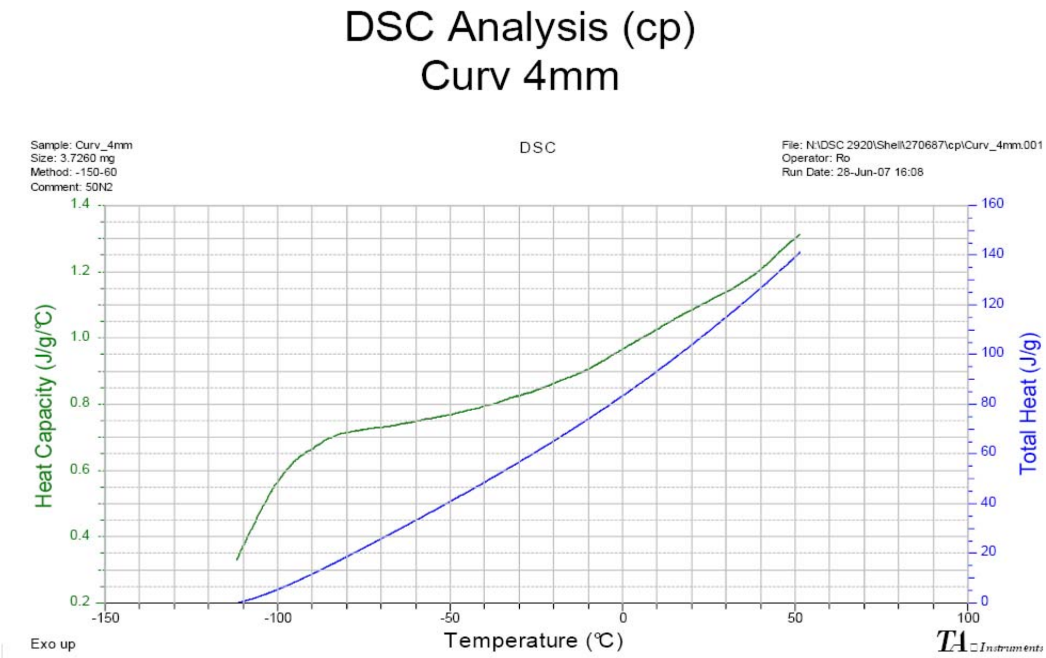


Figure C-3 *DSC scan showing heat capacity of Curv material between –100 °C and 50 °C*

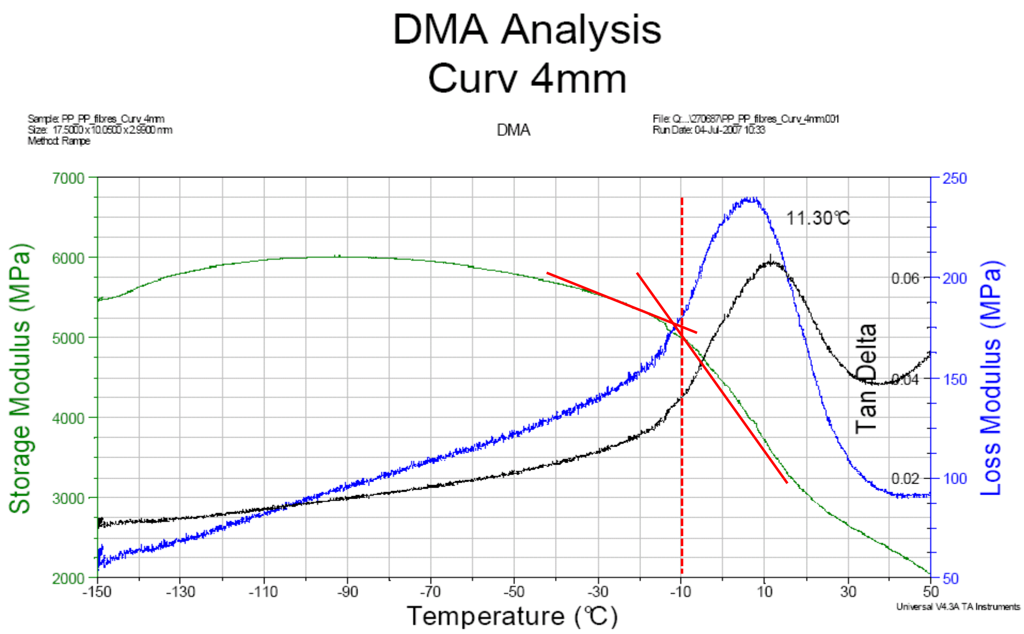


Figure C-4
DMA scan between –150 and 50 °C showing storage modulus drop onset at about -10 °C

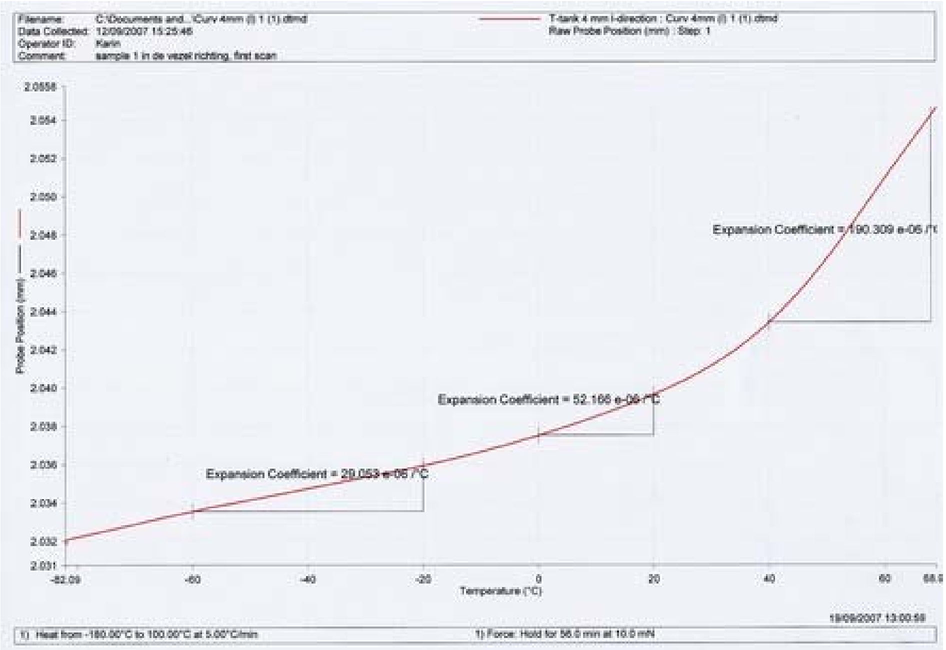
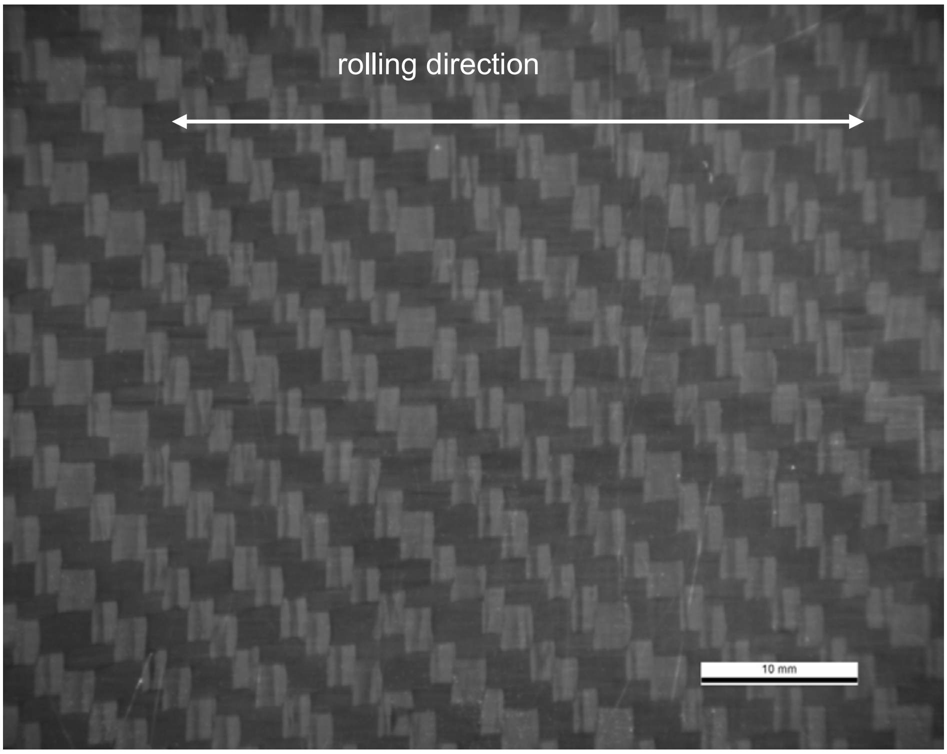
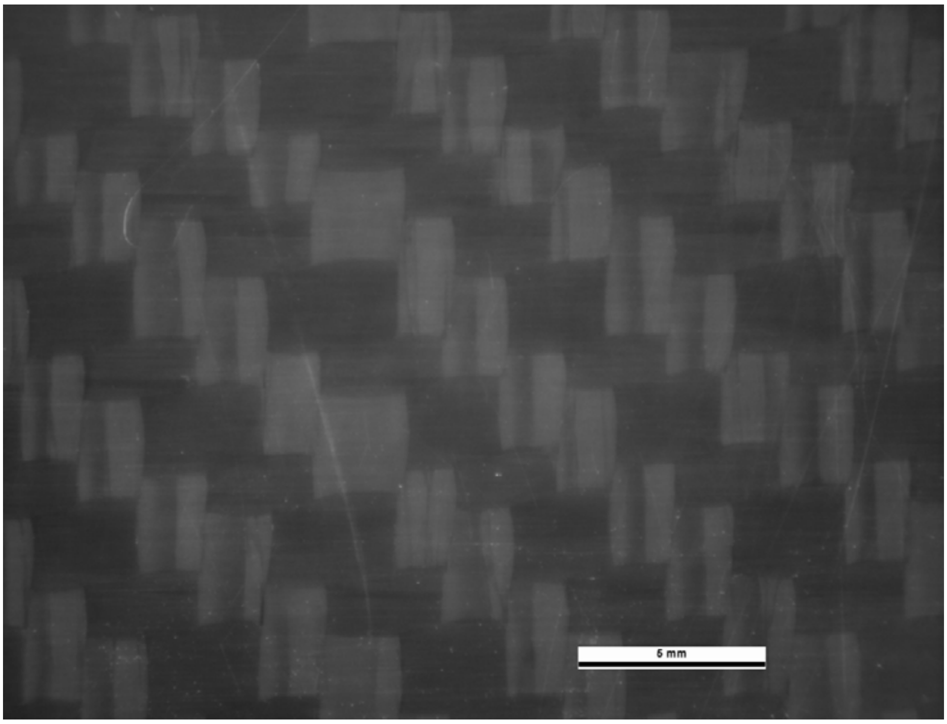


Figure C-5 *TMA scan showing thermal expansion of Curv between –82 and 69 °C*

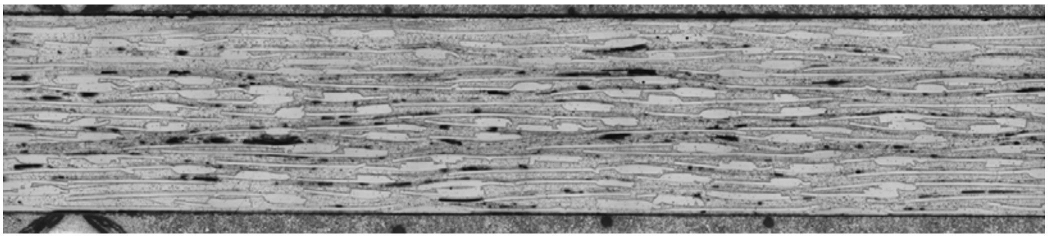


a) overview

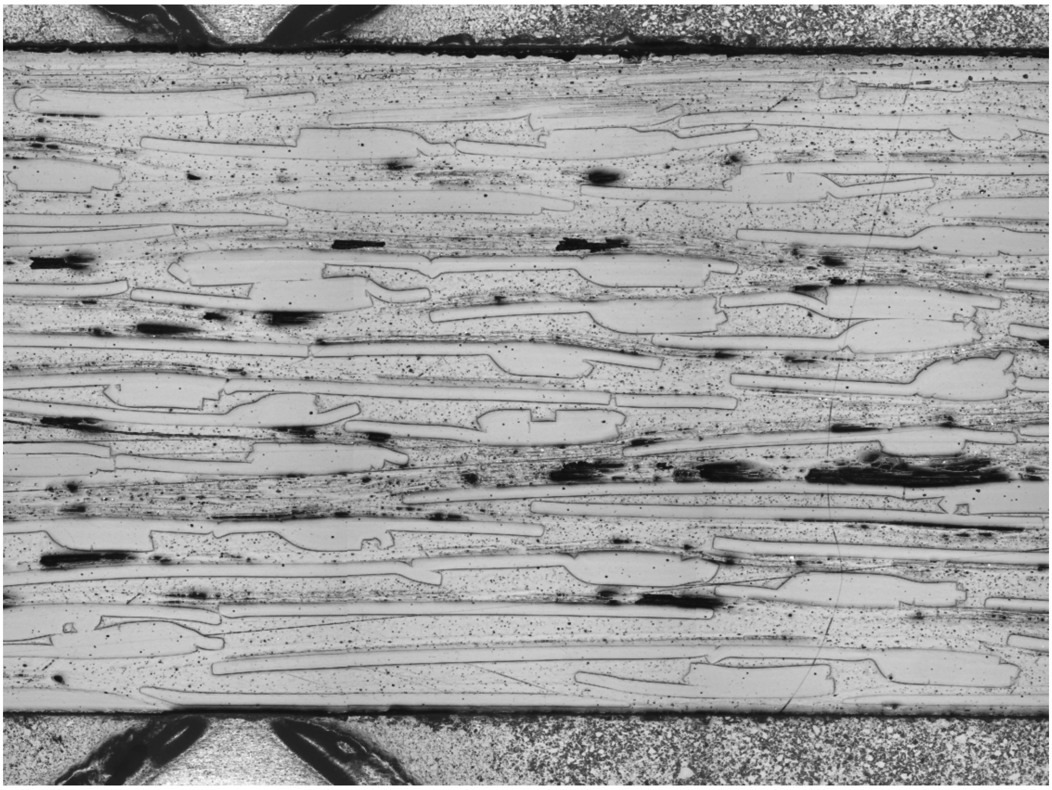


b) close up

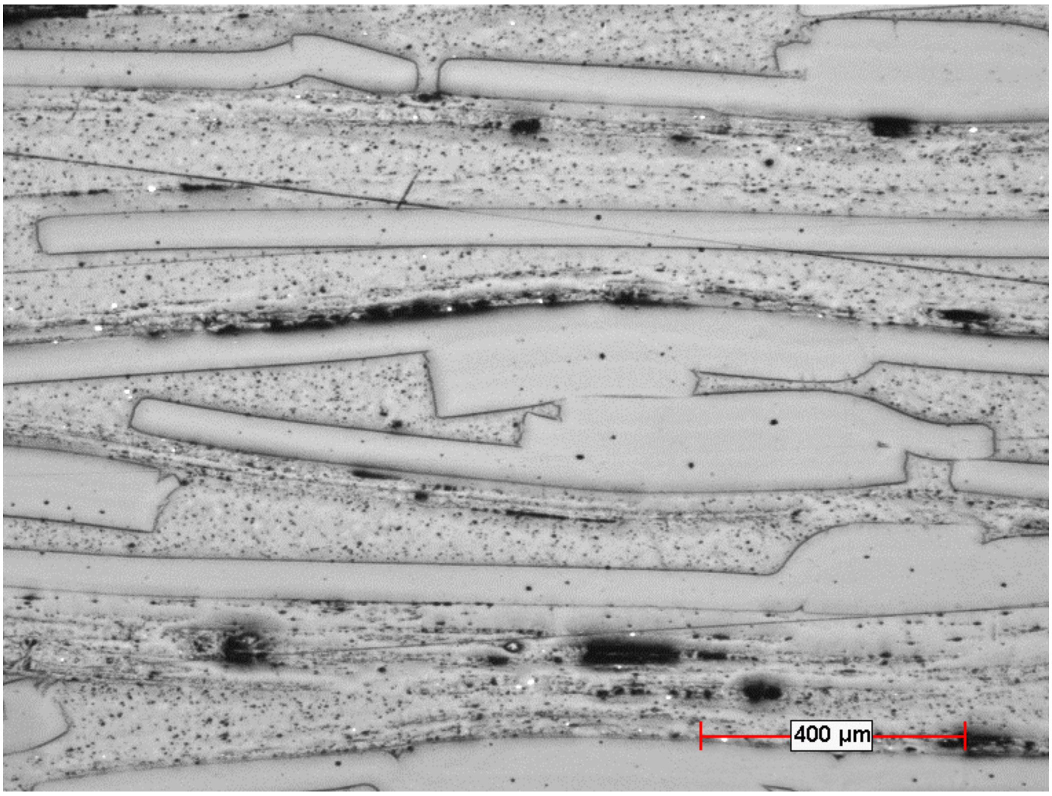
Figure C-6 *Typical surface of a 3 mm thick Curv sheet*



a) cross-section of 16 x 3 mm of a piece of the Curv sheet, showing several layers of the fabric and in-between a matrix of re-melted PP

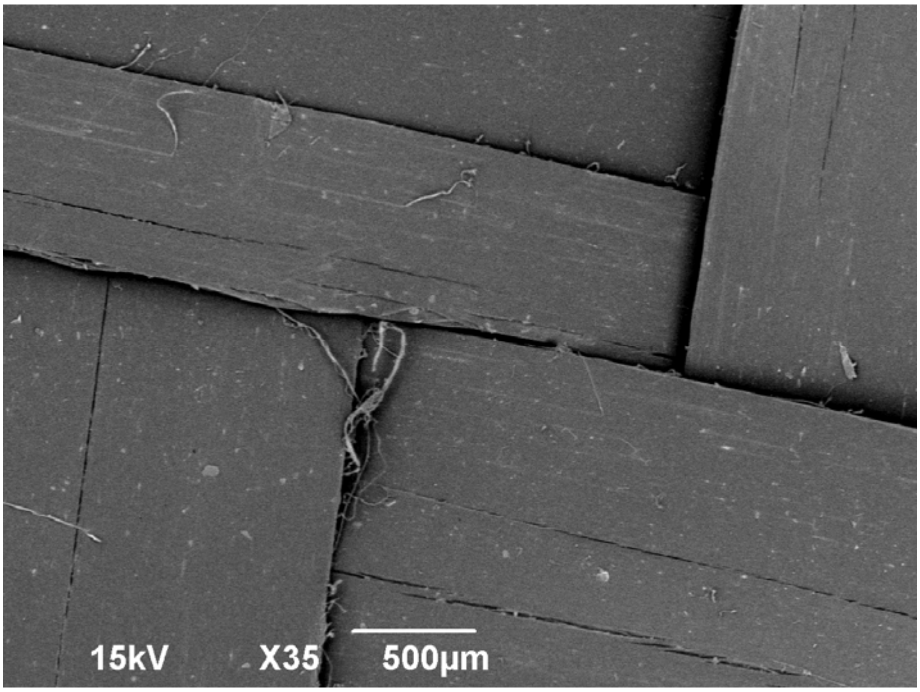


b) close up showing remaining PP strands cut in longitudinal and transverse direction embedded in a matrix of re-melted PP; black patches are voids

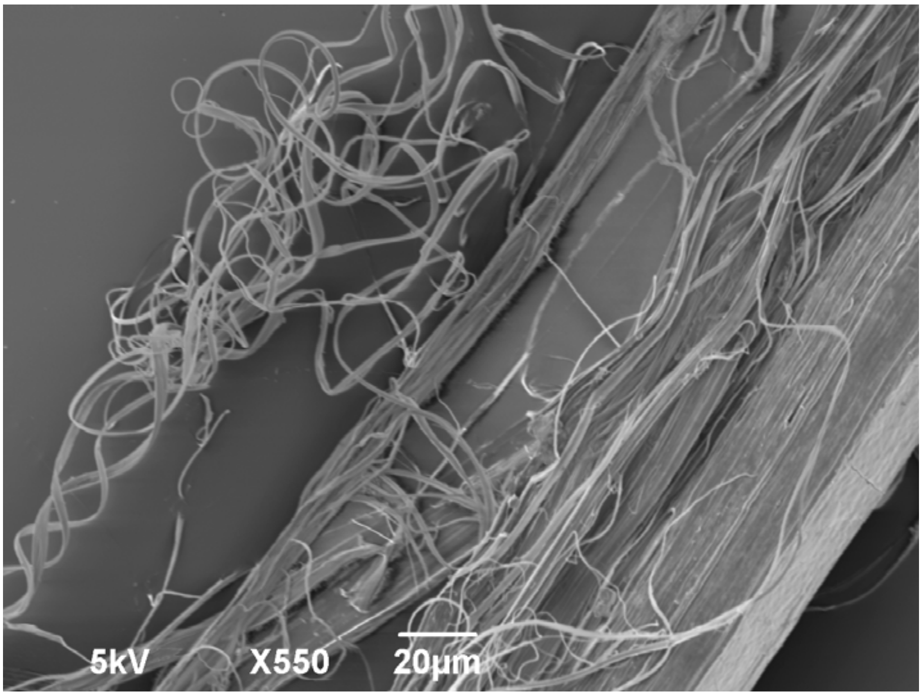


c) close up with high magnification, thickness of the longitudinal strands is about 70µm

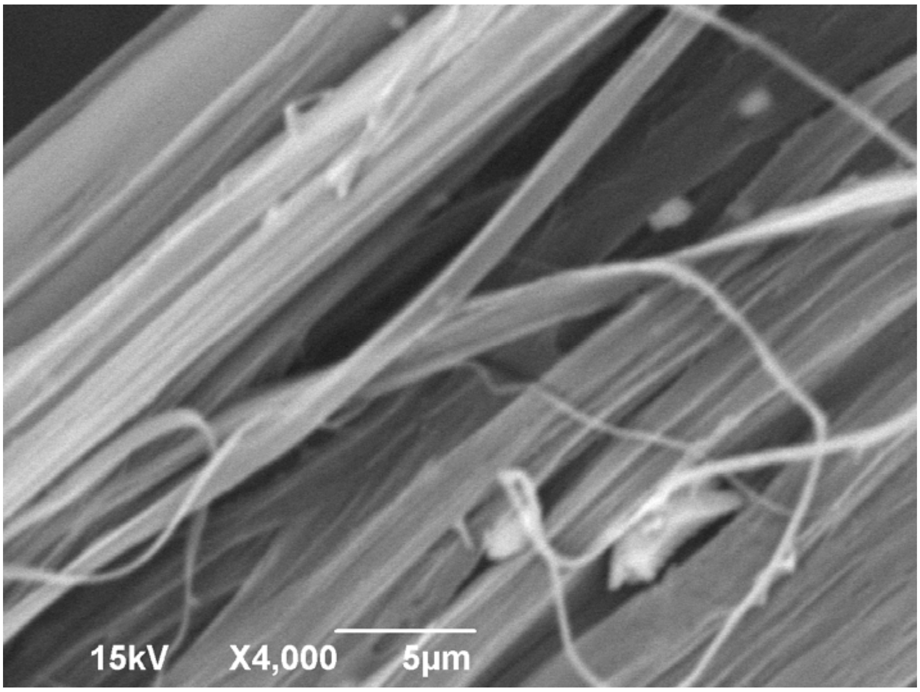
Figure C-7 *Typical microstructure of 3 mm thick Curv sheet cross section*



a) View on the surface of unconsolidated Curv by SEM (BE)



b) Each of the strands is composed of many thin fibres



c) Close up at high magnification shows separate fibres compacted to form a strand; smallest fibre diameter << 1 µm

Figure C-8 *Photographs by SEM showing the structure of unconsolidated Curv*

Appendix D. Test results CURV all-PP sheet material

Appendix D - Results
test programme CURV

Appendix E. Test results DIAB PVC insulation foam

Appendix E - Results
test programme PVC i

Appendix F. Nanoforce: Optimum draw ratio of all-PP tapes

Appendix F -
Nanoforce draw ratio

Appendix G. Nanoforce: Alternative co-extrusion polymers

Appendix G -
Alternative co-extrus

Appendix H. Permeation and fatigue tests TUM

Appendix H -
Permeation and Fatig

Appendix I. Sergem Report – Pre treatment and adhesive bonding of polymer components for cryogenic applications

Appendix I -
Pre-treatment and ac

Appendix J. Sergem Report – Adhesive bonding specimen design and manufacturing

Appendix J -
Adhesive bonding spe

Appendix K. Sergem Report – QA-QC of adhesive bonded joints

Appendix K - QA-QC
adhesive bonds.pdf

Appendix L. Airborne Composites – Proof of concept testing of polymer pipe for cryogenic applications

Appendix L -
Airborne Composites

Bibliographic Information

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