Executive Summary:
Within the project “Integrated Process Chain for Automated and Flexible Production of Fibre-Reinforced Plastic Products (FibreChain)” automated and flexible production systems for the manufacturing of fibre-reinforced thermoplastic composites and multi-material components have been developed, addressing public and private transportation, mechanical, chemical and civil engineering as well as consumer goods.
To achieve a flexible volume production the synergies of efficient primary shaping technologies such as laser-assisted tape placement and reshaping technologies such as thermoforming have been fully exploited. Tape placement enables with a single unit the automated production of large structural components (e.g. fuselages, wings), rotational parts (e.g. pipes, tanks, shafts, tailbooms), tailored composite sheets as well as the local reinforcement of finished and semi-finished goods. Whereas tape placement is one of the most flexible processes available, thermoforming is one of the most productive. Thermoforming enables the reshaping of composite sheets and tubes (tailored, local reinforced or standard) into complex shapes (e.g. car body components, fuel lines) in cycle times of less than a minute.

In conjunction with sophisticated new tools for cutting (laser cutting, milling) and joining (laser joining, welding, fastening) of thermoplastic composites, the utilization of rapid and precise quality assurance tools (laser scanners) and a control environment that is applicable to all main industrial routing systems (joint-arm robot, gantries, machine tools) industrial relevant process chains have been established.

To further synchronize the production of thermoplastic composites with inputs from lean manufacturing, multi-purpose equipment was developed, such as thermoforming systems enabling the in-situ integration of inserts into composite parts within thermoforming and a multi-functional laser source suitable for tape placement, cutting and joining of composites.

The sensitivity of thermoplastic composites to the endured thermal cycles have been taken into account and comprehensive simulation and testing tasks have been performed, to validate and advance process models for performance prediction purposes.

To transfer thermoplastic composites and multi-material systems into major markets also major material innovations have been achieved. Within FibreChain new fibre sizings have been developed that enable cost reduction and increased performance for thermoplastic composites. Furthermore systems and processes have developed that achieve a flexible manufacturing of high performance, unidirectional fibre-reinforced tapes at higher productivity and better quality and a high volume production of low cost, fabric reinforced composite sheets.

The achievements within the FibreChain project have honoured with a JEC Innovation Award 2013 in the process category and the GHTC award 2013 in lightweight design.

Industrial partners have been:
UTC, bf1systems, MX. Composys, Fiberdur, AFPT, TenCate, Suprem, Toray, Nikon Metrology, Trumpf, Missler, Precitec and Strojirna TYC

Research partners have been:
Fraunhofer Institute for Production Technology IPT (coordinator), University of Twente, TWI, Research Center of Manufacturing Technology (RCMT) and the Fraunhofer Institute for Laser Technology ILT

Project Context and Objectives:
Lightweight components are in great demand anywhere, where high performance and efficiency of the materials are required. A typical example in the transport sectors where reduced weight can lead to
Improved fuel consumption and efficiency.

Highly specialised production systems now supply multi-layered, three-dimensional lightweight components made of fibre-reinforced plastics (FRP), but these are only produced for niche applications. A production system that represents an integrated process chain and that can be used across industries and that is capable of mass production has so far not become available.

In the project "Integrative process chain for the automated and flexible production of components made of fibre-reinforced plastics (FibreChain)" a flexible, production system for the production of high performance lightweight and recyclable components of continuous fibre-reinforced thermoplastics.

Such systems have possible application across a wide range of sectors including: automotive, aerospace, shipbuilding, railway engineering and sporting equipment, as well as mechanical and plant engineering, construction, container construction, power engineering.

The aim of the programme is to improve the manufacturing process for continuous aligned fibre-reinforced thermoplastic matrix composites. This improvement will be:

- Improved process quality, reliability and flexibility
- Lower costs
- Increased productivity
- Better 3D structures with increased functionalisation

The interdisciplinary consortium of 18 partners bring their skills from seven European countries in the areas of materials, engineering, manufacturing, measurement and control technology and simulation in the project.

The overall objectives of the programme include:

- The use of UD prepreg material, to avoid the disadvantages of fabrics, notably improved mechanical performance;
- Flexible and automated production;
- Net-shape production with minimum waste;
- Development of laser systems and processes for laser-assisted tape laying, laser cutting and laser welding with a single laser source to create advanced out of autoclave production;
- In-situ integration of inserts during the thermoforming operation with minimal fibre damage;
- Development of optimized process and quality control of prepreg material production;
- Integrate advanced joining techniques into the overall process;
- Quality assurance through automated measurement systems for the production; and
- Establishment of a comprehensive material-and process database and a simulation environment along the process chain.

The project layout comprises a simultaneous development of processes, manufacturing systems, materials, metrology and simulation tools. By this approach e.g. materials are adapted to processes and
vice versa. Furthermore the acquired data from the quality assurance tools is used to improve the manufacturing and machining systems as well as to gain input for the modelling software. By this method accurate process models can be developed that are in line with the experimental results and therefore increasing knowledge, the predictability and hence the trust and applicability of thermoplastic composites.

The central manufacturing processes for the flexible production are laser-assisted tape placement and thermoforming. These main manufacturing processes are embedded in process chains with sophisticated joining and cutting processes and tools. By this method the major component geometry classes such as large scale structural components (e.g. wings, fuselages), developable parts (e.g. pipes, shafts, tanks) and small and complex goods (e.g. battery boxes, housings, car body panels) can be produced lean in an one piece flow approach as well as in a medium scale serial production. In the field of manufacturing systems FibreChain aims at the development of end effectors such as tape placement heads, joining and cutting units, handling devices and forming moulds. These tools are designed to be equipped to available industrial state-of-the-art infrastructure such as joined-arm-robots, machine tools, gantry systems and presses. This will allow manufactures, especially SMEs e.g. from metal working to upgrade their existing systems with goal oriented additional equipment to also supply the composites market with minimum of investments.

The FibreChain approach strengthens the European composite supply as a whole and allows European companies diversification, market and product development as well as additional market penetration in the field of composites. This will make Europe as whole less dependent of metals getting continuously more expensive.

Project Results:
The FibreChain project was divided into twelve work packages. The S&T results are described work package per work package starting from work package 2 as the first work package only included management tasks. Excluded is as well work package 12 which focused on standardization, dissemination and exploitation tasks.

Work package 2:
Definition of generic FRTC part requirements

As a result of work package 2 a catalogue of generic form elements was defined. These have been built into demonstrators as part of work packages 10 and 11. Specification sheets for each element listing the manufacturing processes and subsequent challenges as well as the performance and dimensional requirements were completed. These were accompanied with a full list of engineering drawings.

It was specified that the list of elements would comprise each major product geometry class; large structural components, small and complex parts as well as cylindrical components.

The list of element is shown below:

- Carbon-fibre-reinforced thermoplastic pressurised cylinder manufactured via tape winding
- Carbon-fibre-reinforced thermoplastic cylinder with precision circumferential groove feature
- Carbon-fibre-reinforced thermoplastic pressurised cylinder with bend along the length
Reason for the selection of a number of elements was to compare and contrast against existing state-of-the-art products largely manufactured from thermosetting resins.

The element specification sheets were utilised firstly in defining the manufacturing processes required and subsequently in defining the performance specifications of the chosen processes. Tape winding, tape laying and thermoforming were selected as the core processes. The performance specifications were split into quantitative measures of performance where target values were specified and where this was not possible qualitative characteristics of successful application were identified.

Work package 3:
Layout, modelling, simulation and characterisation of materials, processes and products

The main objective of Work Package 3 was to develop a supporting simulation tool for product design and process optimisation. Furthermore, a database was to be developed for performance prediction of the final part as a function of the precursor properties and the processes used. Both objectives were accomplished.

The whole chain from filament to composite product consists of a range of processes of varying complexity, in terms of multiphysical phenomena as well as in terms of the technology involved in the applications. Various virtual tools were available at the start of the FibreChain project, but a number of missing links still had to be resolved to enable the analysis of the whole chain of processes. Part of these could be resolved by additional physical modelling, others, however, had to be incorporated by a more empirical approach.

Simulation methods were developed for Laser Assisted Tape Placement (LATP), laser cutting and
thermoforming. The models focus on the thermal analysis of these processes, getting input from earlier developed mechanical and optical models.

A detailed 3D finite element model was generated for the laser assisted tape placement process, as an improvement of an earlier developed 1.5D model which lacks the in-plane (transverse to the tape) heat transfer. The model provides very detailed information on the whole process, but is subject to material property data which are difficult to determine experimentally, such as the crystallization rate as a function of the cooling rate. The model is linked to a ray tracing model of the laser heating process, which in turn requires not only the geometry of the set-up, but also the light absorption characteristics as a function of the incident angle and the temperature, which are again material property data difficult to assess. The simulation was embedded in an optimization scheme, to determine e.g. the laser position to obtain the highest possible tape deposition rate, while assuring a proper temperature distribution for sufficient bonding of tape and laminate without overheating the thermoplastic composite material. The total analysis appears to include all relevant physical phenomena, but, as a result, is rather computational intensive.

To enable more extensive parameter studies, a simplified 2D finite volume model was developed as well, to enable fast analyses of the temperature distribution through the thickness of a composite laminate (less than 1 second computational time for a complete cycle of heating up to melt and cooling down to room temperature). This model was applied for the tape placement process, providing a means to quickly evaluate the evolution of the temperature and the cooling rate during the process as a function of different process settings. It is a useful tool for quick estimations of other thermal processes as well, such as laser joining. Further, this 2D thermal model provided the basis for the thermal analysis capability in thermoforming simulations. To this end, it was rewritten in a stand-alone Dynamic Link Library (dll) which can interact as a separate module with an existing commercially available three-dimensional finite element code for composites forming simulations (Aniform) from which it reads the contact conditions and to which it returns the temperature distribution. These temperatures are subsequently used in the forming simulations to adapt the mechanical properties and hence affect the forming behavior. This thermo-mechanical coupling is going to be implemented in a future release of the software, giving direct application of the FibreChain S&T results by an EU SME, accessible for a global audience.

Laser cutting was studied by means of a separate 2D finite element model, including the relevant physical phenomena such as the difference in thermal properties between fibre and matrix, as well as the different evaporation temperatures. The model confirms earlier expectations of the physics involved in laser cutting processes in a quantitative manner, and can be used to improve the process settings by means of virtual experiments.

A wide range of material property data had to be determined to feed the processing models. Optical properties of the thermoplastic were measured for different materials, as a function of temperature. A set-up was created and the corresponding data were obtained for PEEK/T-700 and PA12/T700 tapes. The subsequent heating of the tape materials is strongly heating rate dependent, as the crystallization phenomena (both during heating and cooling) are not instantaneous, but require time for completion. Especially in case of fast processes with short cycle times, such as laser assisted tape placement and stamp forming, the heating and/or cooling rates are far beyond the regularly reported data at e.g. max 20K/min. Measurements were performed using flash-DSC equipment to assess the effects of heating rates up to 1000K/sec on the crystallization kinetics. Novel equipment was assessed to measure heat
conduction transverse to the fibre direction. With these data, complemented with material property data available from literature, it was possible to run the numerical process simulation models.

Development of a physically based model describing the effects of a new sizing on the mechanical performance of the final composite part was clearly beyond the scope of a three-year research project. An empirical approach was chosen instead (WP3.4) assessing critical mechanical performance (short beam shear strength and ±45° tension experiments) as a function of fibre (T700 vs AS4), sizing, resin (PEEK vs PA12) and laminate manufacturing (press consolidation vs tape placement). The new sizing was confirmed to outperform the original sizing for carbon-PEEK, and tape placement processed laminates showed about 15% lower properties compared to the press formed laminates, without extensive process optimization. The elevated level of porosity of the tape placed laminates indicates room for improvement of the tape placement process.

The first steps were taken to investigate the link between tape quality and the performance of a laminate produced by fast laser assisted tape placement processes. An expert assessment was performed in an attempt to identify the critical aspects in tape quality, such as surface roughness, tape geometry, fibre/resin distribution and voids in the tape. As a next step, methods were evaluated to characterize these properties. Different surface characterization methods (confocal microscopy, stylus profiler measurement) were critically assessed, as well as the suitability of various criteria to quantify the surface texture.

The large amount of data generated during the project is of varying nature (qualitative as well as quantitative) and of various levels of standardization (from ISO standards to innovative measurement techniques with little precedence). The data that can be used for quantitative process modelling as well as the data that were obtained following standardized measurement procedures were collected in a comprehensive database for the materials investigated during the project. The database is suited for further extension in future research activities on thermoplastic composites.

Some of the findings have been made publically available as conference contributions. Further work is ongoing to make the results suited for refereed scientific publications, as well as for dissemination to a wider audience in terms of commercially available software for virtual process optimization.

Work package 4:
Precursor development and optimisation (fibres, tapes, plates)

WP4 objectives are the development of the precursor materials (fibres, tapes and plates) optimised according to required characteristics and processing capabilities as well as the determination of optimised process parameters and the research of materials behaviour under precursor process conditions.

In task 4.1 and concurrently with WP2, the raw materials to be used in the project were determined according to technical requirements and availabilities. The state of the art thermoplastic matrix systems, fibre materials and the tapes as those used during the R&D phase were selected. This selection covers almost the complete range of the physical properties from potential fibres and polymers.

The objective of task 4.2 is the development of optimised reinforcement fibres for thermoplastic matrix
systems.

Thermoplastics composites are expanding into automotive and aircraft applications due to many advantages: short cycle time for fabrication, high impact properties, recyclability and so on. The processes of engineering plastics require high temperatures which are not compatible with the conventional fibres. Many companies need to burn sizing off before fabrication or to use unsized yarn.

Toray developed a new thermally stable fibre: mainly T700SC-12K-M0E. During the project, several analyses were performed on the T700S-M0E fibres to prove that the fibre properties are compatible with the thermoplastic process and leads to higher composites properties compared to the state of the art fibres.

The “M” sizing shows a high thermal stability with an onset temperature higher than 450°C which is higher than the typical process temperature of thermoplastic resins.

The excellent compatibility and adhesion to high performance resin matrix was determined and the T700S-M0E fibres show excellent adhesion with PEI resin.

The cross-section observations of tapes manufactured with PEEK and PA12 resins confirm that the “M” sizing has a good compatibility with PEEK and PA12.

The quality of the fibres and the ability to weave them were studied after ageing at ambient temperature and at 40°C. The ageing of the fibres does not impact on the quality and on the ability to weave the fibres.

By developing the “M” sizing, the production cost of laminates could be optimised. Indeed the first step of the process which consisted of the desizing is not necessary anymore. And the adhesion fibre/thermoplastic matrix is improved.

The objectives of task 4.3 are the development of a flexible fibre-reinforced thermoplastic tape production system and the optimisation of tape properties. That means to develop process and optimise parameters in order to provide high quality products adjusted to automated processes, reduce costs while remaining flexible.

Work performed in FibreChain first has led to a much better understanding of the whole complex process and of the technologies involved in the different process steps. It allowed to determine the most critical functions and how they impact each tape characteristic and property. Then new concepts and tools have been developed to improve process and implement a prototype line.

The prototype line demonstrated the ability to increase production to six tapes in parallel while enhancing the parameters setup tape by tape. The unwinding step allowed to settle tension electronically per spool and to get a uniform fibre tension in all rovings in the tape. A new concept of the impregnation function allowed a better manage of a constant polymer content at any time as well as a setup tape by tape. Consolidation has been improved to optimise cooling and tape shape. Winding has also been improved to reach a more uniform coiling.

Process know-how has also been improved through the establishment of work instructions which have enabled to define standardized methods for production preparation, defining the process operations, the good conditioning and defects management. This allowed a better staff training and to proceed accurately, reducing waste and non-conformities.

A system for production management and production database management have been developed,
improving production monitoring and archiving, that will lead to statistical analysis and process capability evaluation.

Finally T700SC-M0E fibres with the new sizing developed by Toray has been introduced in Suprem’s portfolio. Thermoplastic sizing benefit has already been mentioned. In Suprem’s process, the sizing is not burned before processing, the remaining sizing in tapes may degrade in post consolidation operations and create voids. Processing with sized fibre has also a non negligible advantage comparing to unsized fibres as sizing protect fibres, limits their breakage which create whorls but also their spread in different parts of the tools and equipment, generating breakdown or dysfunctions. Moreover, the sizing results in a more stable behaviour of the roving compared to the unsized fibres and directly helps to achieve a more stable process therefore reducing waste.

One of the objectives of WP4 was to develop thermoplastic composites plates with optimised materials and processes, aiming for the reduction of costs of the overall production chain while maintaining equal material performance. Thermoplastic laminates were produced using the newly developed T700-12K-M0E fibre and compared to standard T700-12K fibres and the T300-3K and AS4 benchmark materials. The 12K fibres result in a cost optimisation in two ways: 1. The material and processing costs of 12K fibres are generally lower than of 3K fibres (within in the same fibre class), and 2. The heat treatment of the fibre that is usually needed for the manufacture of thermoplastic composites can be eliminated.

It was shown that the T700-12K-M0E can be well processed using standard carbon fabric weaving looms. It was demonstrated that better properties can be achieved with the T700-12K-M0E fibre when it is used as a reinforcement for an injection moulding grade polyamide 6 (PA6). However, impregnation and wet-out have to be improved for other matrices such a the standard high viscosity PPS used by TenCate.

The production costs of thermoplastic composites can be reduced using automated processing. The cost-efficient manufacture of thermoplastic prepgs by using a powder coating process was evaluated. It was shown that a C/PA prepreg could be well produced using a powder coating technique. The cost-efficient, large volume production of laminates was researched through a desk-top study.

Work package 5:  
Process development and machine optimisation for tape laying/winding and automated handling

Within work package 5 tape placement and handling equipment as well as processes have been developed and optimized.

Within task 5.1 an overall CO2-laser tape placement system for CO2-laser-assisted tape laying has been developed and build up. This system consist of a handling system, a completely new designed highly flexible mirror based 3D beam guiding system, a CO2-laser tape placement unit with integrated optics which allows the active adaption of the width, height and angle of the homogenized laser spot as well as an overall industry ready control architecture and closed-loop control system. This developed system enabled the manufacturing of test laminates made of milky-transparent glass fibre reinforced thermoplastic tapes.

Objective of task 5.2 was the determination and evaluation of maximal possible lay-up rates and most complex part geometries feasible in respect to the used tape parameters.
It was found that the laser-assisted tape placement process is scalable in respect to process speed as long as sufficient laser power and consolidation length is available. The requested laser power and consolidation length depends on the used velocity and material. Longer consolidation lengths result in better weld strength by increasing the available consolidation time at a given lay-up rate.

Only low compaction forces are needed in laser-assisted tape placement as the resulting pressure is only needed to achieve a good contact between two tapes. The needed compaction force is a function of material quality and viscosity and the available consolidation length, time and system.

The process study also included feasibility studies for tape placement of 3D components. From experiments and available literature the following guidelines can be derived. Beneficial tapes for 3D tape placement have a low viscosity, a low fibre content and are as narrow and thin as possible. The process is best steered with low lay-up rates, low pressure and a good first layer fixation. It is obvious that beneficial adjustments for 3D tape placement with the available approach are in contradiction to the high volume production (high lay-up rates, large tape cross section) and high performance components (high fibre volume contents).

The subdivision of a complex shape in three individual curvatures and the further comparison of achievable radii of a given tape with the minimal radii of a part has shown to allow a fast and cheap suitability estimation. The minimal derived radii e.g. are for the smallest FibreChain tape (6 mm x 0.15 mm) are in-plane above 1200 mm and for longitudinal (concave, convex) bending above 0.36 mm.

With the established method to derive the largest processable tape section for a given part geometry in conjunction with the study that enables an estimation of highest lay-up rates with a given system the maximal throughput can be calculated. This has been performed for PA12/CF tapes but the method can be applied to other tape materials as well.

Task 5.3 aimed at providing automated handling solutions for the FibreChain materials, goods and semi-finished parts such as tapes, components and blanks. The tapes are handled mainly by the tape guiding systems which are integrated in the tape placement unit of task 5.1 and which consist of guiding rollers and guiding grooves. For the rigid FRTC parts the octopus gripper of Fraunhofer IPT was further developed and adjusted to be able to handle the FibreChain goods defined in work package 2 such as bent and straight pipes with varying diameters as well as flat, convex and concave bent panels.

The octopus handling device consists of four gripping arms that are attached to a base structure via flexible bearings. The gripping arms are based on the concept of a self-adapting fin-ray gear. The additional attached spring bumpers at the gripping arms allow the handling of concave shaped parts. The gripping itself is realized by either Bernoulli, vacuum, electrostatic or needle grippers that are attached at the gripping arms. Next to the handling of flexible and rigid parts handling devices for thermoforming composite blanks have been developed. For this a tool kit has been developed that enables for every thermorforming operation a fast implementation of suitable handling devices consisting of blank holders, frame structures and tensioning devices.

Task 5.4 focused on the development, manufacture and evaluation of tape-laid reinforcement structures. The possibilities for reinforcement structures producible via tape placement are manifold. Applications can be stringers (ribs) in shell-like structures, axial reinforcements (0° fibres) on tubes, shafts or cantilevers, wound reinforcements on thermoplastics liners (tubes), radial reinforcements for fittings or reinforcement ribs on sandwich panels (e.g. machine door) local reinforcements on blanks. To evaluate the potential of
local reinforcements to manufacture hybrid and multi-material parts, a variety of polymers (PA12, PA 66, PA 6), reinforcements (UD, fabric) and fibre types (carbon [T700, T300, AS4], glass [E6, S2]) have been joint via tape placement and evaluated via the mandrel peel test. The type of carbon (T700, T300, AS4) or glass fibre (E6, S2) and reinforcement type (UD, fabric) had no major impact to the joint strength. Different fibres (glass, carbon) within the to be joined parts can affect the joint strength because of the different degree of laser absorption, if the process is not adjusted from standard parameters. The standard parameters are derived for materials with the same degree of absorption. The main process parameters to adjust the process to different absorption degrees of tape and substrate are the laser angle (either more to the tape or vice versa) and the mould temperature. Best results are obtained if the same polymer and fibre type (same absorbance of laser radiation) in the laminate and tape is available. Strong bonds between different polymers can be achieved if the processing temperature and the viscosity at process temperature of two different polymers in the tape and the substrate are similar.

If two different polymers are joined the process temperature of the more thermal stable material should be used, as long as this temperature is below the degradation temperature of the less thermal stable material.

Therefore: The bond strength achieved in laser-assisted tape placement is the better the more similar the tape and substrate are, in a chemical, thermodynamic and optical sense. However, similarities are beneficial but not always crucial, e.g. with black tapes white blanks could be reinforced.

For the development of the Local Carbon technology, for the laser-assisted integration of local composite reinforcements, and a corresponding business and marketing plan for global industrialization the project coordinator of FibreChain, Alexander Kermer-Meyer received the “German High Tech Champion Award” 2013 in lightweight design.

Within task 5.5 a first layer solution was developed for the laser-assisted tape placement process. The solution for the first layer issue which has been developed in the FibreChain project is based on an adjustable, temperature-controlled and vacuum-assisted lay-up mould. The main idea is to place a thermoplastic film layer between the mould and the first layer of fibre-reinforced tape. The plastic film can be made out of the same material as the matrix of the tape and can be molten by the laser. However, due to the different optical properties for diode laser radiation (940-980 nm), the laser absorption will be different, i.e. lower than the laser absorption of the thermoplastic composite tape. The adhesion between film and mould is be achieved by vacuum. To allow an optimal tape laying process, the mould and film layer have to be heated. A 500 mm x 500 mm mould has been developed and set up. The mould consists of a heating panel on which a micro-porous, air-permeable aluminium plate is mounted. The plate is thermally insulated using an insulating layer. The mould is connected to a vacuum pump so that the thermoplastic film can be sucked to the mould.

The results show that the temperature distribution is very homogenous as the difference between the hottest and lowest temperature value typically is between 1-2 °C.

Furthermore, the detach-force between the thermoplastic film and the mould has been determined by applying a force in perpendicular direction to the mould surface to a 25 mm x 25 mm sized part of CFRP which was attached to the thermoplastic film. The part of the CFRP part matches the standard width of a thermoplastic CFRP-tape. The results show a very strong connection of the plastic film to the mould if an appropriate vacuum is applied in general. The detach-force is higher than 100 N which is the maximum value of the used force gauge. However, if the force is applied to the edge of the thermoplastic film, the film can be peeled of quite easily. To solve this problem, the mould either has to be larger than the tape-
layered area or a stronger vacuum has to be applied.

Work package 6:
Process and mould development for thermoforming

Main objective of task 6.1 was the development of a process that enables the integration of inserts and holes during thermoforming without the destruction of the load carrying fibres in order to enhance the remaining performance of the laminate as well as the joint strength between insert and part. A test rig has been set up that enables the local heating of various blanks and the penetration of variable insert geometries in order to push the fibre aside with limited fibre damage. Inserts have been integrated in moulded holes and drilled holes. Under all tested load cases and with all tested materials the inserts integrated in moulded-in holes achieved higher joint strength. Three load cases have been evaluated: pull out, bending, bearing load. In average inserts in moulded-in holes achieved a 25% higher joint strength.

Main objective of task 6.2 is the development of an energy efficient, precise and flexible heating system for preheating FRTC blanks in FibreChain. Considered methods have been, induction, resistance heating, laser, infrared and hot gas and hot air. In order to allow next to carbon fibre-reinforced blanks also the heating of non conductive blanks, e.g. with low cost glass fibre-reinforcements, induction and resistance heating are not suitable for the FiberChain system. The remaining methods have been evaluated concerning controllability, efficiency and costs.

At the given boundary conditions infrared heating was evaluated as the best practise method for the turnkey system. As a consequence an infrared test rig has been set-up to optimize the closed loop control method for the implementation of a defined temperature profile. The heating and cooling cycles have additionally been modelled for further process optimizations in the field of thermoforming and for the improvements of the used handling devices (clamps). The simulated heating cycles have been verified via an integrated temperature measuring sensor within the blanks.

In additional tests hot air heating systems have been proven to be beneficial for multi-material components as this heating method is independent from optical properties and allows a homogenous heating. The easy distribution of a heat flow by flexible nozzle designs make this method also beneficial to heat up complex (preformed) shapes.

The flexible FibreChain process requires a mould which can be easily exchanged. This challenge has been coped with within task 6.3. As the forming pressure for composite forming is relatively low compared to the pressure during metal forming, the mould does not have to be very rigid. A mould has been designed which consists of a male metal die and a female rubber die. The rubber die can be mounted into a rigid metal frame. The metal die can either be milled as one piece or mounted onto an adapter plate. The later solution is only suitable for non-complex geometries. In both cases, the metal frame can be used for different geometries so that only the cheap rubber part has to be replaced. The mounting of the moulds could be automated by using a standard robot system. However, this is not suitable for the project as the formed geometries are not changed that often.

As not only the moulds have to be changed quickly, a similar approach was applied for the insert system as well which is integrated into the mould. The use of an adapter plate allows to change the insert.
geometry without changing the mould itself. The adapter plate and insert can be mounted to the die either by adhesion or by magnetic force. The exchange of the adapter plate or the insert can easily be automated by using a standard robot system with a conventional gripper system.

Objective of task 6.4 has been the development of a thermoforming mould for in process integration of inserts during thermoforming. A laboratory press has been used for the first demonstration of the thermoforming moulds. The moulds consist of a metal stamp and a female rubber mould. Following the flexible approach described in task 6.3 the inserts can either be mounted in the female or male mould. It is also possible to use the mould without insert integration. The mould has been successfully used to form hat-shaped profiles out of composite laminates with unidirectional and multidirectional fibre orientation. Furthermore, different moulds were used to form a spherical structure as well as a cubical structure. In general, the overall feasibility of the silicone mould has been proven. However, as wrinkling and buckling occurred in complex areas such as sharp edges, further process investigation has been carried out in task 6.5. The silicone moulds have shown their feasibility for the forming of composites with non-uniform thickness as well. Due to the elastic behaviour of the moulds, variations of the blank thickness in tailored blanks can be compensated. Tailored blanks allow the load optimized reinforcement of composite blanks with unidirectional carbon fibre tapes. It is possible to reinforce glass fibre blanks with carbon fibre tapes. The thermoforming of these hybrid blanks has been successfully proven although the heating process had to be adapted to the different material properties.

Due to the flexible approach, the thermoforming mould can be used for the in-situ integration of inserts during the thermoforming process. According to the concept which has been developed in task 6.2 it is possible to mould holes during the forming process instead of drilling them into the formed part afterwards. This process leads to higher joint strength as the fibres are not damaged. Furthermore, no complicated cutting of the abrasive fibres is required. For the proof of this concept, several inserts have been manufactured. The insert itself is a rotational symmetric part with an integrated thread so that other parts can be screwed to the insert. During the moulding-in process, a tip is mounted on top of the insert. The tip spreads the fibres apart so that the insert can be moulded into the composite part without damaging the fibres. To prevent corrosion, especially when aluminium is used as insert material, a thermoplastic sleeve, e.g., a PEEK sleeve, can be used as insulating layer between the carbon fibres and the metal inserts. After the forming process, the tip can be removed.

Several trials have been performed with different composite materials and different locations of the inserts. When the insert is placed into the metal die so that the tip points towards the silicone mould, severe wrinkling and fibre displacement occur if unidirectional composite blanks are formed. It is not possible to mould holes in textile composite blanks using this set-up without large wrinkling and buckling. The silicone mould is too soft to apply the necessary pressure on the areas close to the insert. This problem does not occur when the insert is mounted in the female silicone die. The opposite metal mould supports the composite blank when the tip is punched through the blank so that no wrinkling or buckling occurs.

In task 6.5 finally a process study has been performed. The goal of the analysis is to achieve a better
understanding of the drapeability of composite blanks in respect to material and process parameters. Material parameters that are investigated are different textile reinforcements as crimped fabrics and uncrimped unidirectional reinforcements with different angle arrangements. On the process side mainly the tool temperature and forming pressure are investigated. Evaluation criteria for the investigations are the forming accuracy, the surface quality as well fibre displacements and wrinkles. For the forming investigations a metallic cavity (mould) has been used. The forming pressure was introduced by a silicon stamp (die).

The trials started with fabric reinforced blanks with a quasi-isotropic fibre orientation. The forming results in a good quality in the middle of the part, the forming quality in the edges strongly depends on the location. While the quality at the concave radius is quite good, the pressure was insufficient to form the curvatures and radii at the other locations. The edge radius has been investigated using different positions of the piston. A lower piston position (start of compression) leads to better forming results and the forming radius decreases. With the position of the piston the forming pressure can be influenced. A lower piston position results in a higher forming pressure. Especially the corners are difficult to form. Excessive matrix material is squeezed out of the composite material to the surface.

The comparison of the forming of quasi-isotropic an 0°/90° materials show that the forming capabilities of 0°/90° material is much better as the deviation from the designed form is significantly smaller than for quasi-isotropic material. The results show that the forming properties of UD based materials is somewhere between the quasi isotropic arranged fabric and the 0°/90° fabric material.

Wrinkling at the edges and corners is an effect which occurs for all kind of materials. The influence of the mould temperature and forming pressure has been investigated.

The main results are:
- Increase of mould temperature reduces wrinkling.
- Higher pressure does not prevent wrinkles but presses the wrinkles into the material so that a smooth surface occurs. However, although the wrinkles are less visible they still exist.

For fabrics, the matrix material is squeezed out if the forming pressure is to low and there is no physical contact between the mould and the material.

The effects of matrix squeeze out are not visible for UD-based materials. However, another effect occurs. If the fibres are parallel to the forming edge, a shear off of the first ply can be seen. This does not happen, when the fibres are perpendicular to the forming edge.

Several insert types have been integrated in different laminate structures. The influence of the fibre displacement due to the insert integration will be explained on basis of the used pole bolt. The used pole bolt could be integrated in fabric based and tape based laminates with multidirectional fibre arrangements. Experiments showed that the tension introduced by the blank holders to the laminate has a significant influence to the degree of wrinkles. A higher tension reduces the amount and magnitude of the wrinkles. A higher laminate tension hampers the displacement of the fibers.

Using solely one fibre direction in the laminate, the introduction of an insert results in diamond shaped hole
with a growing crack (matrix failure) along the fibre direction as no fibres are in place to stop the crack propagation. By introducing additional fibre orientations this effect can be eliminated. In a multidirectional laminate a polygon hole structure in the area of the introduced insert is visible. The fibre direction is influenced in area of 30 mm around the insert.

Using fabric reinforcement the area of the fibre displacement is reduced to 20 mm due to the intersection locking of the warp and weft thread. Additionally the amount of broken fibres and wrinkles is reduced. The superior drapeability of the fabric reinforced laminates requests a narrow tolerances of the insert integration tool as otherwise the laminate is deep drawn by the inserts and not penetrated.

Work package 7:
Process, laser and machine development for automated cutting and joining of FRTC

In WP7 processes and equipment for cutting and joining are developed based on laser processing as well as on milling and alternative, non-laser joining techniques. Already existing laser sources as fiber lasers are employed for the process development, but also a new multifunctional Q-switched CO2-laser was developed.

Multifunctional laser source
For the first time a ns-pulse CO2-laser in the kW-class was developed. The laser achieved up to 1.7 kW of pulsed average power and above 200 kW peak power. The laser is based on a standard CO2-laser with a shutter disc mounted in the laser resonator bloc between two focusing bending mirrors. The internal focus is a line focus to reduce the intensity of the laser beam at the disc edges during the on/off switching. The laser can be operated in dual mode: pulsed and continuous wave (cw) by removing the internal shutter disc. The beam quality in both modes is close to fundamental mode. For the q-switch mode various shutter disks with differences in number and width of the slits are available to control the pulse shape and the peak power of the pulses. At the maximal possible peak power used for cutting tests (app. 250 kW) intense plasma formation in the laser focus even in ambient air without processing disturbs the cutting process. The successful parameter regime for cutting CFRP has a moderate/low peak power between 50 and 100 kW. To reach a high average power, repetition rates up to 100 kHz were used.

In FibreChain during cutting of thermoplastic carbon fibre reinforced material the heat affected zone (HAZ) could be minimized down to 100µm with the Q-switched pulsed operation mode of the CO2-laser. In addition to achieve this small HAZ the processing strategy had to be optimized: A multi-pass ablation process with high scan speed > 100 m/min for each pass and a sufficient settling time >1s between passes to avoid heat accumulation is essential for a good cutting quality. Thereby the HAZ is a factor of 5 -10 lower than in single-pass standard cutting. Using the high speed ablation process with CO2 or a single-mode fiber laser in cw mode also reduces the HAZ, but only down to 200µm. The highest effective cutting speed (scan speed / number of passes needed for complete separation) was reached with a 5kW single-mode fiber laser, e.g. for C/PA in 2 mm thickness 17 m/min effective speed. The effective speed with the pulsed CO2-laser at 1.1 kW (max. power for the optimized chopper disk configuration) is in the range of 0.5 m/min. Also scaled to the same power level the process efficiency for cuts with the single-mode fiber laser is, depending on the scan speed, by a factor of 5 to 10 higher than with the CO2 Q-switched laser.
Laser transmission joining of CFRP and GFRP was demonstrated with and without form locking of the CFRP body part. In tensile shear tests strengths of 13 N/mm² were achieved.

Non-laser joining techniques
In order to develop a review of non laser assisted joining a number of techniques have been reviewed and then developed into some feasibility studies to gain a further understanding. An overview described different joint arrangements and potential joining options that could be developed as part of the FibreChain process chain. This has lead to microwave and spin welding to be taken to demonstration.

Microwave welding
The microwave chamber used was a VHM HEPHAISTOS; a high power 10kW, computer controlled, 1m³ internal volume machine supplied by Votsch. Two types of tooling have been used: machined aluminium and freeze cast alumina (FCA). FCA has the advantage of being transparent to microwave radiation, allowing more even energy distribution in the joint.

The use of the microwave showed rapid heating of the joint and good bond strength by using PEEK film at the interface. A number of tests were carried out using a range of different power settings (3-8kW), interface materials (PEEK film and PEEK powder) clamping arrangements and support material (aluminium and FCA). Subsequent Single Lap Shear testing of the joints showed that strengths of 24MPa were achievable using the technique.

Spin welding
The spin welder used was a Hurfurth SW 63/100; a production spin welder research tool capable of speed, pressure, weld time and cooling time variations in order to optimise the process. The spin welding trials used non-standard parts to comply with the testing strategy. Therefore, the standard lower chuck had to be replaced by a vacuum chuck to enable flat laminates to be supported during welding.

To weld aluminium boss to a carbon PEEK laminate the spin rate was kept constant at the maximum (2000rpm) and weld pressure and weld time were varied. The performance of the welding process was determined using a standard pull-off tester (PosiTest AT-A) and strengths in excess of 4MPa were achieved. The processing window for aluminium on carbon PEEK was identified in terms of weld pressure and weld time.

Conclusion
Both microwave and spin welding have been demonstrated to be suitable alternative (to laser) joining techniques for two of the demonstrator parts considered in the FibreChain project.

Milling, drilling, turning
Tools for three machining technologies were developed and/or tested: milling (especially edge trimming), drilling and in-feed turning. Commercially available milling and drilling tools were tested. An appropriate drilling tool was selected and its optimal cutting conditions were tested. An original double helix design of a milling tool made from PCD and carbide was proposed. Prototype of tools were produced and successfully tested. Cutting conditions were optimized for maximal tool life time and minimal total cutting costs. The results were submitted within the deliverable D7.2. The tool performance was demonstrated on a specimen of 2D trimming of a test part and 3D trimming of an aerospace part (presented in the deliverable D11.6). The specific shaped tool for in-feed turning was developed and tested for turning of composite
flanges of straight pressure pipes. Knowledge of the design and cutting conditions of milling and turning tools is among RCMT's main strengths. This will be exploited in the further commercial collaboration of RCMT and industrial customers.

Work package 8:
Development of quality assurance and process control systems

In WP8, an advanced measurement and control system is developed, providing in-process performance monitoring of the FRTC components in production. Different measurement methods were analyzed in order to develop an advanced, precise and reliable metrology system.

WP8 started with the definition of performance requirements for metrology and control systems (Task 8.1) hereof. In the scope of this task, Nikon Metrology scanned FibreChain materials with state-of-the-art laser scanners. The specifications for an integrated measurement system were defined: the metrology and control system consists of a laser scanning solution, thermography sensor, online quality assurance software and CAD/CAM software for simulation and tool path generation.

Data handling and performance is an important aspect in this system. Nikon Metrology and Missler defined data streams and formats for efficient data exchange between the different modules (Task 8.2). Focus was on performance and integrated compatibility within the complete process chain. The results of tasks 8.1 and 8.2 are described in D8.1 "Conceptual design for online metrology and control system and defined requirements for metrology and QA system".

Starting from the specifications defined in Task 8.1 Nikon Metrology developed a laser scanning system for the offline and online acquisition of component geometries (Task 8.3) and for visual quality characteristics such as flashes, edges, surface (Task 8.4) as well as inspection and online quality assurance software for laser scanning (Task 8.5).

In Task 8.3 Nikon Metrology developed solutions for FRPC material related challenges in optical laser scanning, laser scanner robustness and temperature control, as well as laser scanner processing software algorithms. The main results of this task were both integrated into a first laser scanner model with limited field of view that was introduced to the market during the project, and in a new laser scanning prototype with a field-of-view according to the requirements of the FibreChain project.

In Task 8.4 Nikon Metrology developed solutions to obtain more detail on edges, and investigated data acquisition and processing performance. These results were integrated in the new laser scanner prototype. This new laser scanner prototype provides for a higher measurement coverage, in particular on materials that are difficult to scan with optical technologies. For both the robot cell based demonstrator as for the machine cell based demonstrator, a setup with this laser scanner is defined that meets the requirements for optimal visibility and accessibility during inline acquisition. The field of view of the laser scanner as well as the stand-off distance were designed to meet these requirements. The influence of ambient and process temperature on laser scanner was investigated. No complications were expected w.r.t. environmental temperature. Also no significant influence of part temperature was seen in the scanning result. The laser scanner design was optimized to ensure fast warm-up of the laser scanner. In addition, a new temperature model was developed. As a result, the new laser scanner prototype has 0
Nikon Metrology also researched solutions for measurement of edges and flashes. This resulted both in hardware changes, and improved edge detection algorithms that take into account the laser scanner characteristics. Also the research for a new imager in the laser scanner contributed to improved measurement of edges.

In support of integration and demonstration, a laser scanner was used in a manual setup at the robot cell based demonstrator at Fraunhofer IPT, and developments were done to support integration on the machine tool cell based demonstrator at RCMT. Both setups used state-of-the-art laser scanners so as to start the work prior to the availability of the new laser scanning prototype.

For the integration on the machine tool cell demonstrator at RCMT, both RCMT and Strojirna TYC developed solutions for the mechanical and electrical aspects. The first results are described in D8.2 “Offline metrology system and proof of concept for online system”. Nikon Metrology and RCMT jointly investigated triggering solutions for accurate position readout. Nikon Metrology also developed laser scanning processing software for this integration. An important aspect both in the integration, but also in general use of the laser scanner, is the data acquisition performance and required bandwidth. In the new laser scanner, the data transfer is increased with factor 2.9.

In Task 8.5 Nikon Metrology developed algorithms for laser scanning inspection software. These include alignment algorithms for automatic post-processing of scanned data into polygonal mesh, edge point detection and novel feature detection algorithms. The first Task 8.5 results were described in D8.3 “Online metrology and quality assurance software for laser-assisted tape-laying”. The final results of tasks 8.3 8.4 and 8.5 are described in D8.4 “Online metrology and quality assurance system for integration in entire process chain”.

The laser scanning technology is used before each FibreChain process to adjust the process if required, during tape laying after each ply for later analysis of issues, and after each process to validate the process outcome.

During blank production, and application of reinforcement, thermography is used. Therefore a thermography sensor (Task 8.4) and online software (Task 8.5) is developed by Precitec. In Task 8.4 Precitec analysed technical parameters of different sensor devices, defined a new hardware concept, and integrated this concept in the process chain. In Task 8.5 Precitec developed a „free programmable“ monitoring system for supervision and control of laser processes using IR camera technology. Both image processing algorithms as well as a new GUI were developed.

In addition, as the laser cutting business is one of the main pillars of Precitec, Precitec developed new solutions for distance control in cutting operations. The distance of the cutting tool, typically a laser cutting head, to the work piece surface is one of the main parameters to get a good quality cut. After several studies, a sensor system based on low-coherence interferometry emerged and was implemented in the cutting process.

The adjustment of processes is done in the CAD/CAM system. Missler developed new CAD/CAM functionality for FibreChain turnkey manufacturing systems in Task 8.6 hereto. The work starts from
Missler’s CAD/CAM software TopSolid. Functionality that already existed in TopSolid was directly tested. The work in FibreChain both focused on CAD comparison of the laser scanning data, and on support of specific operations like tape laying and laser cutting.

The laser scanning that is done before each FibreChain process results in a point cloud. Missler has developed new algorithms to work with this measurement data and compare with the target CAD part model to evaluate the extra material area resulting from the tape laying process. This module is then used to control manufactured pieces and to indicate what zones in the part are wrong and to improve the manufacturing procedure for the next pass where possible.

In support of the tape laying process, Fraunhofer ILT and Missler developed solutions to manage laser technology by adapting parameters and by tool path calculation. The new solutions consist of both simulation algorithms and algorithms for the generation of CNC code for this specific process. Whereas CAD/CAM systems by design mostly support classic configurations of CNC machines, this new module required the investigation and implementation of a robotic module. In addition, an interface was developed to send the tool path information to the robotic module prototype.

New algorithms were also developed to simulate the cutting process, including collision detection, both for milling machines as robots. Models of the machine were provided by the WP 8 partners where available. Other were designed in TopSolid, such as the Reis robot at Fraunhofer ILT and the CNC machine at RCMT.

Although these new innovations are specific for the FibreChain project, they can be used in a wider range of CAD/CAM applications in an industrial environment. New CAD/CAM software is also available to manage all robots and machines used in the FibreChain project. The results are described in D8.5 “CAD/CAM environment for the FibreChain turnkey systems”.

Work package 9:
Process chain design and component integration

WP9 covered the hard- and software configuration of the integrated process chain in order to achieve a flexible and automated production of multi-layered 3D-shaped components based on flexible FRTC prepregs. WP9 focused on ensuring the smooth concurrence of the individual components to achieve realistic and applicable turnkey manufacturing solutions. Two research partners (RCMT, IPT) and nine industrial partners (AFPT, TWI, TRUMPF, FIBREDUR, MX, SUPREM, TYC, MISSLER, NIKON - producers of technologies and devices or end-users) were involved in the WP activities.

The task T9.1 activities focused on overall system design & derivation of equipment requirements. The main input was a list of performance specifications for the manufacturing systems defined in the deliverable D2.3. Following this, production roadmaps of all demonstrator parts (specification of technological steps) were described. The process chain generally consists of five main headstones: product specification (size, shape, functionality), material (the product is made from), process (series of specific technologies for modifying the blank into final part), tool and machine (machine performs the technology using a specific tool). The process chain design for all demonstrator parts was described; that means that all materials & blanks, processes, tools and machines necessary for the production of the
specific demonstration parts were mentioned. It was a general overview that makes a basis for a specific manufacturing plan. The results were submitted within the deliverable D9.1.

The task T9.2 activities focused on the definition of interfaces. Every technology needs specific equipment for its realization. There were three types of manufacturing equipment within the Fibrechain project: tool (it makes the process), machine (it carries the tool and workpiece) and supporting device (it supports the whole process; this category includes various clamping devices, steady rests, additional control tools etc.). Next, tool mechanical interfaces (mechanical connectors: size, position; fluid connectors: fluid type, connector size and type; electrical connectors: power and signal connectors), control and communication strategy (tool depends on the machine – on-line communication is necessary, master/slave role must be defined OR tool is independent of the machine – off-line communication during post-processing phase; also related communication compatibility such as protocols and data formats) were described in the deliverable D9.1. This was an important information if a decision is made about what machine type is able to use the tool (machine tool or robot, single-technology or multifunctional machine).

The results of the task T9.1 and the task T9.2 described in the deliverable D9.1 were used for activities within the task T9.3 that was focused on development of an assembly strategy. The main scope of the work was a description of a complex manufacturing and assembly system structure. The proposed structure was demonstrated on complex demonstrator parts which consist of elementary generic technological features. Integration of all these elementary technologies into one complex production process was described in the deliverable D9.2. The results showed that integration of complex machines and tools (winding/laying head, laser scanner, machine tool, and robot) is possible.

Following this, modules and integration into turnkey systems was defined within the task T9.4. The results were presented in the deliverable D9.3. The specific production modules were defined. Combination and connection of these modules enable to create a functionally integrated process chain for the production of a specific demonstrator part. The compatibility of all production chain components is based on previous work summarized in the deliverable D9.1. All three documents/deliverables provide a comprehensive overview of technologies for the production of FRP parts and possibilities for their integration. The deliverable D9.3 was the last step in the production system planning. Related activities continued within WP10 “Validation and optimization of systems, processes and entire process chains” and within WP10 “Demonstration”.

Systematic description of relations and interfaces for building a turnkey manufacturing solutions is the main result of the WP9. The findings within the WP9 work helped to support development of specific technologies and their integration possibilities within WP5, WP6, WP7 and WP8. The result demonstrated within WP11 is a unique combination of technologies and machines (robot-based and machine tool-based integrated process chain) for automated turnkey production of the FRP parts.

Work package 10: Validation and optimisation of systems, processes and entire process chains

In WP10 the single processes as well as the whole process chain have been investigated and optimised. A focus was on the optimisation of the interfaces between the process steps and the interdependencies of
the processes. The individual production stations have been synchronised in order to demonstrate the feasibility of the process chain integration.

In task 10.1 all functionalities of the processes have been analyzed. As a result an adjustment requirement list has been established comprising the needed work to do, in order to be able to produce the demonstrator parts. According to the adjustment requirements list the processes and systems have been enhanced to meet all the needed specifications to manufacture the demonstrator parts as defined in WP2 (task 10.2).

The main idea of task 10.3 was to elaborate if it is feasible to take the heat, time and pressure of a secondary forming process into account in order to increase the lay-up rate of the primary tape placement process, and therefore to increase the productivity of the process chain. Also it was evaluated how suitable local reinforcements are and what benefits can be achieved. Also it is a matter of interest if the placed fiber angles influence the thermoforming process.

Various tests have been performed to qualify the consolidation in order to give a profound overview. Lay-up rates 300 mm/s to 500 mm/s have been tested. The faster robot was not available for the experiments. However a faster robot is also not requested as with the used materials and laser optic, the available laser power limits the process speed to 500 mm/s. The cross section analysis as well as the three point bending tests showed no difference in optical, quality, bending strength and bending stiffness in respect to the lay-up and post-consolidation process. This highlights that cross section analysis and standard 3-point bending tests are unsuited to characterise the consolidation of tape placed layers.

Using two better suited tests for the evaluation of the interlaminar shear strength (ILSS) as a short beam test and a mandrel peel test the sensitivities become obvious. Having sufficient laser-energy available, there is hardly a difference between the consolidations, which means an “in-situ” consolidation was achieved. When not sufficient laser power is available (= the process speed is to fast) the ILSS values of the reinforced panels are reduced whereas the re-formed panels showed the same strength as the direct “in-situ” consolidated panels. This means, that if there is a secondary forming process, the local reinforcements do not have to be fully-consolidated to achieve optimal values in the final product.

In the tested scenario it could be demonstrated the lay-up rate in tape placement can be increased by at least 67 % without compromising the quality when the interdependencies of tape placement and thermoforming are taken into account. Additional it could be demonstrated that the bending stiffness and strength can be locally increased by 59 % and 22 % respectively just adding a single carbon-fibre reinforced tape layer to an approx. 2 mm thick glass-fiber reinforced laminate. With the demonstrated lay-up rate of 500 mm/s, 30 m of local reinforcements can be placed within an automotive cycle time of one minute, with material costs of 14.4 cent per meter reinforcement. Further the failure mode changes from brittle failure to a ductile failure mode, which is beneficial for crash behaviour and safety relevant parts.

Additional the influence of the fiber-orientation in forming wound (pre-formed) laminates was evaluated. Here it became obvious that it is best to use only two fiber angles such as e.g. ± 45°, ± 55° or ± 65°. Such
orientations allow a relative movement between fibers.

It could be demonstrated that the productivity and efficiency of the process chain can be significantly improved, if the interdependencies of the main FibreChain processes tape placement and thermoforming are taken into account. Furthermore it could be demonstrated that cross section analysis and three-point bending tests are unsuited to evaluate the consolidation quality. In cross section analyses only the compaction and porosity but not the diffusion is visible. Three point bending tests introduce the a pressure load into the fibers in the area of the pressure fin. As a result the parts break under compressive kinking of the fibers (micro-buckling) independent of the reached consolidation. Well suited tests are the short beam test as well as the mandrel peel test as both test introduce the load in the to be tested welding zone.

Task 10.4 aimed at identifying and visualizing economic improvements and (if possible) at deriving break even values (amount, time) of the FibreChain process chains in respect to selected demonstrator parts (see work package 2) of the different product classes tape winding, tape laying and thermoforming. Therefore the demonstrator parts pressurized tube, non-rotary thin walled part and complex non-rotary thin walled part were chosen.

The cost-effectiveness of the FibreChain process chains is compared to state-of-the-art processes in order to underline economic differences. This economical analysis is performed based on data which has been delivered by the relevant project partners or which has already been acquired in other work packages. Specifications that have been taken into account are, for example, production rates, energy consumption or initial investment cost.

The implementation of the economical analysis can mainly be divided up into four parts, which are: collection of process data, recording of detailed cost structure, calculation of the defined cost positions and evaluation of the results. These steps were conducted for the FibreChain process chain as well as for the state-of-the-art process chain for one demonstrator part per product class. As some of the regarded production plants do not yet exist at the moment the collected data was partially based on assumptions and appraisals by the corresponding technology experts.

During the first step, collection of process data, the relevant partners were asked to name the process steps for production of demonstrator parts, used workstations, lot sizes as well as times required for workstation operation, manual labour and set-up. Subsequently information about used material (cost, amount per part) and about detailed cost positions for each workstation was collected. For every workstation the following facts have been taken into account:

- Initial investment cost and interest rate
- Required space per machine and occupancy costs
- Maintenance costs
- Machine performance and electricity rate
- Costs per tool and tooling endurance
- Required workers per shift and labour costs

Afterwards the costs for the positions labour, material, set-up as well as fixed and variable costs were
calculated. Fixed costs consist of depreciation costs, interest costs, occupancy costs and maintenance costs. Variable costs include energy and tooling costs.

Other cost positions such as indirect material costs or indirect administration costs have been excluded from the present economical analysis as they are not influenced by the selection of production processes. Finally, after calculation of the several cost positions, the overall results of the economical analysis for every demonstrator part have been derived and the cost structures of the different process chains (FibreChain, state-of-the-art) were compared.

The pressurized tube, which is a demonstration part of the category »rotary axis-symmetrical part«, is produced by tape winding. Within the state-of-the-art process glass filament and epoxy resin are used as raw materials. In the primary process part the composite layers are winded around a mandrel, with a lot size of three. Subsequently each pipe is cut to length with the help of a lathe and finally the pipe geometry is inspected.

The FibreChain process chain consists of the steps tape preparation, tool preparation, tape placement and product after treatment. The lot size is one for all steps except tape placement. The tape placement is a continuous process that means a continuous pipe is produced that has to be cut to length in order to obtain individual parts. As raw material within the FibreChain process CF PA12 with a fibre volume content of 55% is used.

By applying the method described in the former chapter on the received data production costs per piece in dependence of the annual production output have been calculated for the state-of-the-art and the FibreChain processes. For high production outputs production costs using the FibreChain plant are slightly higher than those using the state-of-the-art process chain. If the annual production outputs are relatively small, below 100.000 pieces, utilizing state-of-the-art-production plant is more economically sensible. Nevertheless using FibreChain production process could be beneficial because of the advantageous properties of the used material and the high production speed. This before-mentioned aspect leads to a very high annual production output of more than 200.00 pieces. In contrast, state-of-the-art annual production output is 14.000 pieces which is less than one fourth. To produce higher quantities per year it would be necessary to operate the machines in two or three shifts or to purchase one or more additional sets of machines.

Since the state-of-the-art and FibreChain process chains are completely different there are high cost differences in terms of fixed, labour and set-up costs, with the cause being the use of different production plants. Furthermore the material costs are different because of the use of thermoplastics as raw material for FibreChain process instead of glass filament. Raw material is a main cost driver for the FibreChain process because of the high quality of the used thermoplastics which results in advantageous component properties such as high damage tolerance. Fixed costs are the second highest cost position because the initial investment costs are very high.

In future FibreChain process costs are expected to decrease because of an increasing use of fibre-reinforced materials with the result that prices of raw materials as well as initial investment costs for production plants will be lowered down. That implies that the FibreChain production process will become more economically competitive.

The non-rotary thin walled part, the chosen demonstrator part for tape laying, is produced by tape
placement. In this chapter the mainly manual state-of-the-art process of conventional tape laying of thermosets is compared to the laser-assisted tape laying of thermoplastics. It can easily be seen from the elaborated charts that energy consumption of laser-assisted thermoplastic tape laying is less than half of the conventional thermoset tape laying. The main factors contributing to energy savings are the cease of the autoclaving and refrigeration steps within the laser-assisted tape laying process. The refrigeration step is necessary for conventional tape laying because the raw material, a preimpragnated matrix has to be stored at -20 °C to prevent a reaction of the resin with the hardening agent. During the autoclaving step the single laminate layers are cured and consolidated. It can be seen that the process cost savings amount to 14 % with omitting of the autoclaving and refrigeration steps being the main reasons. Although different raw materials are used for conventional (thermosets) and laser-assisted tape laying (thermoplastics, e.g. CF-PA12 55% fibre volume content) materials cost roughly the same. Personnel costs, costs for the tape laying head and the used robot or kinematics are also approximately equal for both processes. Additional costs for the laser-assisted in contrast to conventional tape laying arise from the use of a laser or infrared emitter to consolidate the laminate sheets and the need to heat the mould. In conclusion laser-assisted tape laying of fibre-reinforced thermoplastics turns out to be a promising and innovative process with the potential to cut energy consumption and process costs required for production of non-rotary thin walled parts.

The complex non-rotary thin walled part is produced by thermoforming of T300/ PA6 sheets with a thickness of 1mm and a fibre volume content of 55%. The state-of-the-art as well as the FibreChain process chain consist of the steps loading, heating and thermoforming of raw material, which are executed in a thermoforming machine. Subsequently the parts are hemmed with the help of a milling machine. For state-of-the art process chain the last step includes assembling of the thermoformed part with inserts and finishing. For the FibreChain process assembling can already be done during hemming step because a special tool is deployed. In order to derive dependence of production costs per piece from the annual production output the method described in the former chapter has been applied. The result is shown in the line graph in figure 6. It can be seen that process costs per piece using FibreChain process chain are slightly lower than current process costs regardless of annual production output.

In conclusion the developed FibreChain processes are competitive with conventional processes in all three demonstrator parts analysed. The raw materials are a major cost driver due to high quality requirements on finished parts. With increasing use of fibre-reinforced materials and products, raw materials as well as production plants are expected to get less expensive.

In task 10.5 it was shown that a robot based and machine tool based manufacturing system is possible and available for demonstration tasks. A demonstration level TRL 6 (system/subsystem model or prototype demonstration in a relevant environment) till TRL9 (Actual system proven through successful mission operations) has been reached.

Work package 11:
Demonstration of FibreChain
WP11 objectives are the demonstration of the achieved developments and improvements of R&D task of the FibreChain-project.

In Task 11.1 at the start of the project some challenging sample-products were defined. In Task 11.12 almost all defined samples could be realised with satisfying results, proving the opportunities of fibre-reinforced products as a future industrial product ready to be produced in mid-size and larger series:

• Structural panels were produced and locally reinforced and formed afterwards with satisfying specifications
• Pressurised pipes were produced, partly machined and tested afterwards;
• Pipes were bended after winding and compared with a pipe produced on a bended mandrel with promising results
• For a first time a transmission-shaft with welded flanges was defined and produced

In Task 11.2 the possibilities of flexible and stable handling of two and three-dimensional parts with automated and semi-automated newly developed and enhanced handling devices has been demonstrated during the production of the demonstrator parts.

In Task 11.3 an offline and online metrology, quality assurance system and control system were demonstrated.

Laser scanning tests were carried out on products with different complexity. These proved good results compared with tactile probing and sufficient accuracy in scanning edges. In a robot-based manufacturing cell a portable scanner was installed and scanning was done in support of the tape laying process, in support of thermoforming and in support of integration of inserts. The results were used for further optimization of these processes. Also scanners were integrated with CNC machines and demonstrated in lab-conditions successfully. Further work remains to develop the human-machine-interface for easier industrial implementation.

During trials with lasers on cutting and welding it became clear that the cutting process needs to be controlled. The resolution for this is sufficient. For easy adjustment to measurement data from laser scanning in the CAD/CAM system, basic CAD comparison functionality was integrated in the control-software. Also this functionality was successfully demonstrated.

Challenge in Task 11.4 was to prove the adjusted performance of new precursor materials. The new T700SC-12K-M0E T700 has a higher strength and is cheaper than the traditional sizing. Except for that fibre breakage and process malfunctions are reduced and the sized fibres show a more stable behaviour than unsized fibres. This all increases process stability during impregnation.

A prototype of a new tape-production-line proved increased productivity. The modular concept can be adapted to the actual demand. A standardized production management and process surveillance system is developed.

In Task 11.5 in-situ integration of inserts in a thermoforming mould is demonstrated. The joining strength is validated and the results are benchmarked against traditional technologies. The new technology has proven its feasibility and benefits.
Demonstration of the optimized milling tools for FRTP machining was the main objective in the task 11.6. An original double helix design of a milling tool made from PCD and carbide was proposed. Prototypes of tools were produced and successfully tested. Tool performance was demonstrated on a specimen of 2D trimming of a test part and 3D trimming of an aerospace part. Good results in the machining technology opened up a possibility for RCMT of collaborating with other companies outside the project consortium on the development of their machining technologies. Moreover, the collaboration with the TGS company (cutting tools producer) on serial production of the developed tools and LATECOERE Czech Republic (producer of aerospace parts) on machining process optimization is under negotiation. There have also been other requests for collaboration with RCMT from tooling, automotive and aerospace companies. The Fibrechain project has enabled RCMT to be one step ahead of industrial needs. The results have been disseminated within WP11 in technical magazine articles (2) and at trade fairs (1).

Task 11.7 involves the demonstration of an adjustable, temperature-controlled and vacuum-assisted lay-up mould. A plastic film is used to fix the first layer in thermoplastic tape laying and to fulfill specific chemical and optical requirements. In a series of draping tests is carried out under different process conditions. As a result, the drapability has been quantified in regard to the material properties and the film thickness. Furthermore, the homogeneity of the temperature distribution has been determined. The temperature of the mould surface is very homogeneous and can be controlled accurately. Good consolidation has been achieved between the thermoplastic film and the composite structure. The accurate temperature control as well as the good homogeneity of the temperature distribution on the mould surface allow to minimize the distortion of the composite structure.

In Task 11.8 for the first time for cutting composite-material, a ns-pulse CO2-laser in the kW-class is developed. The laser achieves up to 1.7 kW of pulsed average power and above 200 kW peak power. The laser can be operated in dual mode: pulsed and continuous wave (cw) by removing the internal shutter disc. Different tests have been carried out to reduce the number of passes needed for a complete separation of the material. It is proven that a high scan speed is necessary.

In Task 11.9 a laser tape placement system for CO2-laser assisted tape placement including a flexible beam guidance could be integrated into the gantry robot. Each mirror of the guidance was adjusted to realise the irradiation of the process area by the laser beam with rectangular spot geometry exactly at that point where it is needed in any position of the tape placement unit. The verification of the flexibility of the system by turning the orientation of the tape placement unit and thereby the testing of the complete functionality of the telescopic beam coupling was conducted. After checking and validating the overall functionality of the tape placement system, the holistic system was used to investigate and improve the system. Some demonstrator parts (see 11.12) were produced.

In Task 11.10 laser cutting and joining processes and units for integration are demonstrated. Demonstrators are produced:
• with spin-welding: this seems to be the most efficient method of joining circular parts. It is a simple, fast and flexible process that can easily be automated
• by a microwave-process: this is still a relatively immature technology which promises great advantages in speed and efficiency, especially for the automotive market. Critical is pressure during application and
thermal runaway must be prevented.

Task 11.11 demonstrated the use of CO2-laser cutting and joining. Laser processes for CFRP cutting need to employ high average laser power to achieve economical speeds and adequate processing methods to minimize thermal effects on the cut edge.

Using the new developed high power Q-switched CO2-laser (Task 11.8) and fiber lasers (multi-mode and single-mode up to 5 kW), process development for laser cutting of thermoplastic CFRP revealed a reduction of the heat affected zone to 100 µm with the CO2-laser and to 200 µm with the fiber laser. Improvements in cut quality came along with effective processing speeds up to 17 m/min for 2 mm thick Carbon/PA laminates with the fiber laser. The process was demonstrated on flat sheets and on thermoformed parts. It is essential to use a multi-pass ablation process with high processing speed in each pass. A speed >100 m/min should be achieved to ensure good quality, although this might be limited by machine dynamics in contours. Appropriate process windows for the pulse parameters of the Q-switched laser were found with pulse peak power between 50 and 100 kW. A high peak power is preferred for ablation with low heat impact, but it is limited by intense plasma formation due to high intensity.

Laser transmission joining of CFRP with GFRP was demonstrated with and without form locking of the CFRP body part. The maximum load before fracture in shear-tensile tests was 13 N/mm².

The equipment developed for FibreChain comprises new nozzles with integrated suction and a distance measurement system based on optical coherence tomography, since the standard capacitive distance control in cutting is limited to use with metals.

In Task 11.13 a software-based performance prediction tool and database for industrial application is shown. As showcase, a stamp forming process simulation with thermal analysis is used. During demonstration thermal analysis has been added to the structural forming process simulation. By help of the simulation, the effects of material property temperature dependency can be evaluated during the design process. The simulation results are available through a state-of-the-art graphical user interface. By comparing the results during demonstration, in Task 11.14 could be concluded that competitive and superior part performance can be achieved with FibreChain processes and materials. In some cases the necessity for further research work was detected in order to be competitive.

Potential Impact:
Fibre production
Thermoplastics composites are expanding into automotive and aircraft applications due to many advantages. So far the carbon fibers were developed for thermoset composites and the properties and process were not optimised to be used with thermoplastics.

This collaborative project allowed Toray to work with different partners all along the chain of the process not only directly with the direct users of the carbon fiber. Toray developed a new thermally stable fiber T700SC-12K-M0E to answer to the problematic of the customers' process. During the project several analyses were performed on the optimized fibers to prove that the fiber properties are compatible with the thermoplastic process and leads to higher composites properties compared to the state-of-the-art fibers. Toray has some close collaboration with some potential customers for this fiber and could have access to a newt market.
Thanks to the project, Toray received many feedbacks from the partners especially from Suprem and TenCate about the process-ability, impregnation, and performance of our products. So Toray could have better knowledge of the customer’s needs. On the other hand, TenCate and the University of Twente performed some comparisons on the mechanical properties of our materials compared to the state-of-the-art materials that allow us to have a data base with Toray fibers and the process of the partners.

Toray has a better view on the potential applications but the socio-economic impact is difficult to estimate as long as there is no industrial production yet.

Our fiber was appreciated by the users like Suprem and TenCate. For example, Suprem points out the advantages for them to use our material with their process:

- In terms of better processability: The process stability is increased and the produced tape are more regular.
- In term of costs: the optimized fiber is cheaper than the current fiber.

Toray proposed to the partners some long term stability data which could be used by the partners to have a better understanding and perspective on Toray materials.

Tape production

Work performed in FibreChain led to a highly better management and tracking of the production. Indeed, improvement and standardization of internal methods allows to operate following accurate procedures. The development of a system of production management permits an efficient setup and traceability of production parameters as well as of properties measured and a better management of non-conformities and defects. Technical and scientific analysis conducted to a better understanding and mastering of the process. Technological improvements led to an easiest parameters setting, and particularly a setup tape by tape to overcome variations from a fibre roving to other, as well as a more stable process. Direct impact form these results is the security of high quality products delivery, waste reduction and therefore a relation of confidence with customers together with a growth of demand and the evolution from R&D manufacturing to production manufacturing.

Furthermore, the work performed resulted in the doubling of the capacity to meet this demand. It has been demonstrated the possibility to produce six narrow tapes in parallel instead of three with the same process and impregnation line, limiting energy consumption increase. The production system management allows to master this growth without a need of additional resources. That shows Suprem’s ability to increase its capacity to meet growing demand. The choice of a modular system allows Suprem to continue to offer a broad combination of tapes. Next closed step will be to separate R&D from production and generate a production line for industrial products and big productions while a R&D line would be in charge of smaller ones and R&D works. In a slightly more distant future, the demonstration of the doubling of productivity conducts Suprem to the perspective of a multiplication of the number of lines and assured us that we can manage the increase through investment and employment.

Partnership with Toray conducted to the commercialisation of different tapes reinforced with the new sized fibre developed by Toray in this project for several customers. A big amount of our products contains now this fibre. Sizing provided higher process stability and a better processability.

Laminate production
Thermoplastic composites are a very promising class of materials that can be used for the lightweight design in large volume industries such as the automotive industries. The material is still under evaluation in the automotive industry, where thermoplastic composites have been accepted by the aerospace industry since 15 years. The main reason for this is the cost of the material. This cost consists of the costs of the raw materials, the costs involved with the manufacture of thermoplastic laminates and the cost of the forming and finishing of a part.

The FibreChain project has aimed for an integrated approach to optimise the process chain from start to end, or from raw materials to final part. The project offered TenCate the possibility to evaluate materials and processes with a good cost-performance ratio and see the materials produced be evaluated throughout the complete process chain. The introduction of the T700-12K fibre through the project has spun-off to different customer projects in the automotive industry, and to internal screening projects for aerospace applications. An example for a customer project is the realisation of a carbon fibre reinforced thermoplastic wheel, which is based on the T700-12K fibres that were formerly not available within TenCate Advanced Composites. Another example is the development of a very cost-attractive carbon fibre reinforced PP material for an engine protection plate. This product is also based on the T700-12K fibre. The aerospace industry is moving towards a more efficient and cost-driven phase in the application of composites, hence heavier tow fibres such as 6K and 12K bundles, are under evaluation. In conclusion, a result of the Fibrechain project is that the T700-12K is “on-the-shelf” at TenCate, which accelerates future developments.

The evaluation of optimised processes, such as powdercoating of thermoplastic prepregs and the continuous consolidation of laminates using a double belt press, has lead to the basis of the “factory of the future” for TenCate. The basic principles of the processes are now known. The implementation of the processes depends on the market development: the capital investments involved require a certain minimum material volume.

As a material supplier, TenCate is confronted with the need for a complete and detailed overview of the process chain when dealing with the automotive industry. The FibreChain project gives the right insight. This insight is considered as crucial for the adaptation of thermoplastic composites by the large volume industry in the coming 5 years. Automated production of materials and parts using highly skilled labour is the key factor for a competitive position of an European production company such a TenCate Advanced Composites BV within a global environment. The knowledge that has been built up within the FibreChain consortium, together with the network of the FiberChain partners, is needed to grow the market for thermoplastic composites, both in Europe as globally. The creation of jobs depends on the level of automation that can be reached in a high wages country such as the Netherlands.

Tape laying
For Fraunhofer IPT the FibreChain project has been a huge success. The following exploitable results have been achieved in field of tape laying

- The mechanical performance of tape placed laminates could be increased by 8% due better process understanding. Therefore the performance of tape placed laminates could be enhanced from close to compression moulded parts to superior to compression moulded parts. This has been proven on basis on
PA12/CF laminates. This makes the process more beneficial.

- Laminate warpage now can be fully controlled and compensated. This makes the process more applicable.
- Crystallinity of laminates can be estimated with high accuracy before the production. This makes the process more predictable.
- Best process parameters can be chosen on basis of fundamental material data. This reduces costs and time for the determination of the best process parameters.
- The best suitable tape dimensions for tape placement can now estimated by analysing the part geometry according an new established model. This reduces the needed time and money for the evaluation as part geometries and tape widths can be excluded before the mould manufacturing and test trials.
- For the first time tailored laminates with varying fibre-reinforcements, polymers and optical appearances have been produced. This makes the process more flexible.
- The lay-up for the production of tailored blanks could be increased by 69% by taken into account the secondary thermoforming process. Additionally it was demonstrated that with a single carbon fibre-reinforced tape layer on standard glass fibre-reinforced laminate the local bending stiffness and strength is increased by 59% and 22%, respectively. Therefor the benefits and possibility of multi-material tailored blanks has been proven for the first time. Therefore efficiency and flexibility could be further enhanced.
- The first layer issue in tape placement was solved, by applying a plastic film as first layer on a vacuum-assisted micro-porous aluminum mould. This further increased the applicability of the process.

The advancements of the tape placement process have been made public in twelve FibreChain publications as well as showing produced demonstrator parts on international fairs. The achievements in the manufacturing of tailored laminates have been honored with the GHTC award. Due to achievements and dissemination work on laser-assisted tape placement already projects have been contracted by the oil & gas industry, automotive and chemical industry. Significant return on invest was already achieved on this topic during the project and more is to come. Additionally new constitutive research projects have been acquired to further increase the producibility and tailored blanks and three-dimensional tape based parts.

Tape winding

The close cooperation with different partners throughout the “FibreChain” was a great opportunity to verify the economic impact and future road map for AFPT’s tape-placement technology. Based on the input by potential customers and suppliers of raw material AFPT could improve its strategies for tape-placement and based on that could refine the geometric specifications for a new generation of tape-heads.

To simplify the integration of AFPT’s tape-heads in an industrial “FibreChain”, AFPT could compare and select most accepted industrial standards and did start the conversion of its control system. An example for this it the internal standard for integrating future thermo camera’s and AFPT’s improve control system and GUI.

With help of these developments with help of RTCM, AFPT proved that integration of the tape-placement system also is possible in a state-of-the-art CNC-environment, strongly increasing the applications of fibre-placement in industry.

In cooperation with Fiberdur AFPT was able to prove the technical and economic opportunity to reinforce tubes for transportation of fluids and gas. In close partnership with UTC, AFPT did succeed to deliver...
different high-tech semi-finished products to be used for high strength applications like drive shafts.

Technical and scientific analysis of the results during the production of demonstrators conducted to a better understanding and mastering of the tape-placement-process. By improved parameters setting a more stable production-process could be reached, resulting in less waste and a higher and more reliable output of AFPT’s tape-placement-process.

The close cooperation with suppliers of raw material like Suprem gave a better understanding on the impact of the tape-quality on the final characteristics of AFPT’s endproducts. Challenged by the feedback of industrial partners and the preliminary results from WP10, AFPT could develop several concepts for mid- and large-scale production of fibre-reinforced thermoplastic products which will strengthen AFPT’s market-position in the mid- and long-term.

Thermorforming and functionalization
Due to FibreChain Fraunhofer IPT set-up its first thermoforming and functionalization stations and therefore was able to integrate several new technologies and services to its portfolio. Achievements have been:

• Set up of the first thermoforming station specially designed to bend tape wound composite pipes. By this approach thermoforming was enhanced to reshaping 3D preforms instead of 2D preforms. As only a one single-sided mould was needed to from different angles and diameters, tooling cost are comparatively low.
• First process study on thermoforming tubes and pipes have been performed, identifying the crucial parameters and the best test set up.
• Set-up of the first thermoforming station with in-situ integration of inserts and holes during the part-shaping process.
• Validation of the feasibility and performance related benefits of the in-situ integration of inserts has been performed
• First analysis and comparison was done on fibre-displacement in forming fabric, tape based and local-reinforced blanks identifying the crucial parameters.

The advancement in thermoforming has been made public by publications and demonstrators shown at fairs. Constitutive research projects have been acquired. Industrial attention is high but contracts are still pending, as the technology is in rather early state.

Handling
Within FibreChain the existing self-adapting octopus-gripper for draping and handling textile of Fraunhofer IPT has been adapted to handle all kinds of FibreChain goods as straight and pipes with varying angles and diameters as well concave, convex and straight panels. Further handling devices (clamps, frames, tensioners) for thermoforming have been established that enable a flexible and an automated production of composite parts with reduces wrinkles. The exploitation and dissemination is closely linked to thermoforming.

Laser source
The responsibility of TRUMPF within the project was the development of a laser source, which can be operated in continuous wave operation as well as in a short pulse operation. This is an important new
feature for an industrial CO2-Laser. It is the first known system operating at that power level in both operation modes. Before those short pulsed lasers (~ 500 ns) were only available in the multi-hundred Watt regime and not in the 1 to 2 kW class.

At a power level above 1 kW such systems are reaching a level, were a new field of industrial applications is opening. TRUMPF as the leading manufacturer of CO2-Laser covers a wide power range with its products; the lowest available power level is just this limit: 1000 W. This is an indication, that this power is typically needed for many industrial applications of CO2-lasers.

In which way this new developed laser can indeed been used as an industrial tool and whether it will be a commercial success is too early to judge. The partners doing the application test were able to get promising results, but there are still problems, which were not solved with that new tool. As a laser company TRUMPF is not overconfident but usually in laser history, newly developed systems with new characteristics and property soon led to new applications and thus to new markets.

Laser processes
Cutting and joining techniques that were developed in FibreChain have the potential to substitute manual finishing process steps by automated processes at reduced production costs. Cutting without tool wear with a multifunctional laser, which can also be used for consolidation, or cutting with reduced wear by new developed milling tools complete the process chain demonstrated in FibreChain. Due to the versatile need of cutting, trimming and joining operations on nearly all CFRP parts, the potential impact affects a wide range of thermoplastic CFRP applications. For automotive industry e.g. concrete plans to use laser cutting for the production of CFRP parts are followed. By the improvement in processing the usage of CFRP for lightweight design is stimulated and the energy conserving potential using lightweight materials can be exploited under better technical and economic conditions.

The results from FibreChain are an important basis for the ILT for further development of laser processing of fiber reinforced polymers. Further scientific orientated projects are planned to expand the know how gathered in FibreChain to other materials (e.g. glassfiber and different matrix systems) and to push the process limits forward. In bilateral projects with customers from industry the application-oriented developments will be forced. First projects are already running for the automotive industry in the field of cutting of thermoplastic and thermoset CFRP.

Welding
The work carried out in the FibreChain project has led to an advancement of the knowledge on two welding techniques for thermoplastic composites; microwave and spin welding. Incorporation of these non-laser based techniques into the FibreChain process cell ensures the greater flexibility of the process and makes it more attractive to a wider range of potential end users.

The direct impact of the result of the project is the development of new microwave welding technology that has the potential to be exploited widely in the automotive industry. TWI is pursuing the technique and building on the FibreChain result by developing integrated systems for microwave welding for industries such a high volume automotive. Microwave heating can offer significant environmental advantages over competing heating technologies as it is a high efficiency process, resulting in lower power consumption and fewer emissions of greenhouse gasses. It may also be possible to reduce the weight of automotive structures through the uptake of lower cost/high volume manufacturing through microwaves, which will
have an additional beneficial effect on the environment.

TWI has completed several dissemination activities during the project and these will continue after the project closes. The main scientific dissemination activities have been conference presentations; notably the presentation of a paper on microwave welding at the 2014 EECM conference in Seville Spain (June 2014). As a member based R&D organisation TWI is constantly interacting with its membership throughout the word. These members represent all industry sectors and are an ideal route to exploiting the results of the project. There is a growing interest in microwave technology and this has been reflected in more opportunities to discuss the approach with representative of TWI’s membership.

Other broader dissemination activities have included attendance at some of Europe’s largest composites trade fairs (JEC) which enabled TWI to discuss the project in general and the two non-laser based welding technologies with a wide range of representatives from the European and global composites industries.

TWI will also maintain and update the FibreChain web site (www.fibrechain.eu) for a period of five years after the end of the project, enabling all partners to continue dissemination and exploitation of the project results.

Milling & machine tools
Development of cutting tools for FRTP machining was the main objective in the task 7.6. Commercially available milling and drilling tools were tested. An appropriate drilling tool was selected and its optimal cutting conditions were tested. An original double helix design of a milling tool made from PCD and carbide was proposed. Prototypes of tools were produced and successfully tested. Cutting conditions were optimized for maximal tool life time and minimal total cutting costs. Tool performance was demonstrated on a specimen of 2D trimming of a test part and 3D trimming of an aerospace part. The specific shaped tool for in-feed turning was developed and tested for turning of composite flanges of straight pressure pipes. Good results in all machining technologies opened up a possibility for RCMT of collaborating with other companies outside the project consortium on the development of their machining technologies. Moreover, the collaboration with the TGS company on serial production of the developed tools is under negotiation. There have also been other requests for collaboration with RCMT from automotive and aerospace companies. The Fibrechain project has enabled RCMT to be one step ahead of industrial needs. The results have been disseminated in scientific papers (3), technical magazine article (2) and at trade fairs (1).

The Fibrechain project gave the RCMT team an opportunity to collaborate with European technological leaders. Combining the know-how of RCMT and other partners brought four main exploitable results in the following categories: tools for FRTP cutting, tape placement using a machine tool, laser scanning using a machine tool, and design of production systems for FRTP part production.

Development of cutting tools for FRTP machining was an important RCMT task within the Fibrechain project in the WP7. Commercially available milling and drilling tools were tested. An appropriate drilling tool was selected and its optimal cutting conditions were tested. An original double helix design of a milling tool made from PCD and carbide was proposed. Prototypes of tools were produced and successfully tested. Cutting conditions were optimized for maximal tool life time and minimal total cutting costs. Tool performance was demonstrated on a specimen of 2D trimming of a test part and 3D trimming of an aerospace part.
aerospace part. A specific shaped tool for in-feed turning was developed and tested for turning of composite flanges of straight pressure pipes. Good results in all machining technologies opened up a possibility for RCMT of collaborating with other companies outside the project consortium on the development of their machining technologies. Moreover, collaboration with the TGS company on serial production of the developed tools is under negotiation. There have also been other requests for collaboration with RCMT from automotive and aerospace companies. The Fibrechain project has enabled RCMT to be one step ahead of industrial needs. The results have been disseminated in scientific papers, technical magazine articles and at trade fairs.

The integration of the AFPT company tape placement head into a machine tool was a unique challenge that was successfully completed within the project (activity in WP9 and WP12). The integration realized in collaboration with RCMT-AFPT-SAHOS (partner outside the consortium) demonstrated a new promising solution for productive and accurate production of large FRTP parts. The solution was disseminated through technical magazine articles and trade fairs.

Integration of the Nikon Metrology company laser scanner into a machine tool was another unique challenge (activity in WP8 and WP12). The scanner was for the first time integrated and operated in a machine tool equipped with a standard control system. This success opens up new opportunities in the setup of machining processes for RCMT, Nikon Metrology and TYC. The solution needs further development of the human-machine-interface. The demonstrated results enabled the mentioned partners to start negotiation with their customers about the specific application of this system. The solution was disseminated through technical magazine article and fairs.

RCMT acquired knowledge of the modules of the integrated process chain. RCMT has now expertise in systematic design of the customized production chains for the production of FRTP parts based on machine tools. This know-how gives RCMT a good position for participating in new industrial and development projects focused on this progressive materials.

The Strojirna Tyc company can now provide new products after finishing the FibreChain project. Thanks to project they have finished design of special interface between standard machines and new technology devices, which were developed during project. It means new opportunities and markets as well as new customers. Strojirna Tyc designed and produced special accessories for montage of this interface and can do complete testing and geometrical measurement with the same equipment. Strojirna Tyc is bow ready for service and maintenance the new technology for potential customers.

Strojirna Tyc employees obtained many new contacts from companies around European union. It’s a very important experience to be part of a project with international consortium. Strojirna Tyc are sure about benefits in personal growth. They trust to cooperation with some members of project consortium.

Simulation

The S&T results have first of all contributed to a better understanding of thermoplastic composite manufacturing methods, and the requirements to the materials, design and manufacturing methods to reach good performance of the thermoplastic composite products. As known on beforehand, the interplay between design, production and materials is complicated and further steps are needed to make this information available for current and future design in composites, leading to shorter time-to-market by reducing time intensive trial-and-error developments. Quantitative methods and data are required to accomplish this aim.
The FibreChain project has made significant contributions to this field, especially in terms of:

- A fast thermal solver, which is suited for process optimization and control in highly complex production processes such as the laser assisted tape placement process. The potential of this efficient building block can be explored in future R&T activities.
- The coupling of this thermal solver to a commercially available composites forming simulation package, enabling fully coupled non-isothermal press forming analyses at the expense of little extra cpu time. This development has the potential of becoming the state-of-the-art virtual tool for design for manufacturing in thermoplastic composites. The added functionality has already proved to highlight pitfalls and possibilities for process optimization in thermoforming operations. The efficiency of the solution method makes this functionality in reach for practical purposes.
- The materials database provides a first comprehensive overview of the material properties needed for virtual product and process optimization in thermoplastic composites, as well as it contains the required data to perform these virtual optimisations for the materials investigated within the FibreChain project.

With this information, first of all the FibreChain industrial partners have access to advanced foreground results to make their thermoplastic composite developments more efficient and more effective. The research institutes and academic partners have improved their knowledge position in the field. And finally, the connection to an innovative SME as the Aniform company made it possible to integrate new functionality in commercially available software, to be used in Design For Manufacturing strategies in thermoplastic composites. This step ensures the actual exploitation of the simulation developments, and secures the results for future applications (more than an academic exercise for internal use only). FibreChain partners have the right to explore this functionality in a trial version of the software.

The scientific results will be submitted to internationally respected peer reviewed journals after some further fine tuning, leading to improved scientific understanding of thermoplastic composites processing on the global level.

Laser scanning
The laser scanning solutions developed by Nikon Metrology in WP8 were successfully demonstrated both under laboratory conditions as in the FibreChain demonstrator setups. Laser scanning was demonstrated in support of the tape laying/winding process in WP5 and in support of the thermoforming process and integration of inserts in WP6. Nikon Metrology will further develop the new laser scanning prototype and inspection software into a marketable product. Hand over to production is foreseen in 2015. Nikon Metrology’s laser scanner production is done in Derby, UK. Also key suppliers are European. The products will be sold via Nikon Metrology’s world wide sales channel (direct sales) and preferred partners (indirect sales).

The novel concept of the laser scanner integration into the machine tool was successfully tested at RCMT. Further work remains to develop the human-machine-interface for easier industrial implementation. The FibreChain demonstrator provides an excellent starting point for further business case development for “on machine verification”.

Nikon Metrology’s marketing department will take care of market announcements on the website.
(www.nikonmetrology.com) on major exhibitions such as Euromold (Frankfurt, http://www.euromold.com) and Control (Stuttgart, http://www.control-messe.de/control/) internal and external newsletters and external publications.

Process monitoring
The project result will enable Precitec to complete their range of process monitoring systems with new commercial devices for monitoring/controlling the cutting and welding process of fiber reinforced materials. The output of the work will enter into the current and future palette of processing heads and will make them capable to be used for the specific applications addressed in FiberChain. Precitec can definitely use this project to get access to many important end users, which can use the fiber reinforced components in the future to optimise their quality.

Precitec’s exploitation activities have been performed during final phases of the project and for a period of at least one year after the end of the project aiming to create maximum benefit. Commercial exploitation relates to all cross-functional exploitable results of FiberChain. Precitec will encompass sales activities for products manufactured with the know-how of the developed technologies via
• trade fairs and exhibitions to address and acquire new customers by presenting new products and innovations manufactured with the FiberChain technologies
• the marketing and sales channels of Precitec
• publications issued by Precitec and/or the technology network of the RTD performers
• active participation in industrial seminars and networks to communicate selected exploitable results

The potential end users of the FiberChain technologies will gain maximum output of their manufacturing process. Compared to the state-of-the-art the processes are controlled and scrap will be avoided. This definitely will help Precitec to remain as one of the leaders as a manufacturer of laser cutting technology in Europe.

CAD/CAM
Missler, on a corporate level, has gained new knowledge on composite laying and use of robots in machining such material. Some software modules have been developed in these fields and researcher have gained also a personal in depth knowledge of these technologies.
The project had a positive impact on the management towards future strategic decision on the application of robots in machining for dedicated applications.

Motorsport and aerospace engineering
bf1systems are a motorsport and aerospace engineering company that provide solutions to our clients’ challenges. bf1systems is continuously looking at new technologies to explore whether they can deliver novel solutions. Thermoplastic composites have been marketed for nearly 30 years with limited success and bf1systems joined the consortium to help understand the issues that have prevented their widespread adoption, despite their notable advantages.

Participating in FibreChain has allowed bf1systems to identify and explore many of these issues in detail with the consortium partners, and to participate in the development of some exciting solutions to them. Although many of these issues have proven to be more challenging than could be solved inside the
project, FibreChain has allowed bf1 systems to be confident in proposing realistic development schedules to exploit these ideas. Building on what was learnt during the project bf1 systems seeks to progress this work further by investigating laser-cut, tape-laid preforms that can be thermoformed into parts that are too complex to manufacture using current state-of-the-art techniques.

The opportunity to learn from all the consortium partners has been fantastic and led to further opportunities. bf1 systems wishes to work with TWI to explore microwave welding of TP composites. TenCate has supplied bf1 systems with materials that are being investigated within an aerospace research programme bf1 systems is undertaking with an aerospace OEM. In addition AFTP have shown to bf1 systems capabilities that would allow one of bf1 systems technologies to be improved by adapting it to use thermoplastic composites.

Chemical engineering

High pressure pipe systems with a high chemical resistance are required by the petrochemical industry. As until today high pressure glass fibre reinforced thermoplastic pipe systems with a thermoplastic only matrix are not available on the market.

Researching and developing such a glass fibre reinforced thermoplastic pipe system would massively improve the maintenance, durability and environmental safety for pipe systems with critical liquids where today high alloy steel is used with more or less average success.

This project allowed Fiberdur to work with different partners who have consolidated knowledge in the field of robot supported laser welding and machining of thermoplastic and thermoset products. During the developing process of the demonstrator high pressure pipes and connections, there was a great knowledge transfer between the partners. Thanks to this project we as a manufacturer of thermoset pipes and prospective end user of a production chain for reinforced thermoset pipes were able to gain a better understanding and knowledge about the state of the art of laser welding technology and the build up of a laser production chain. On the other hand we have shared our knowledge with the project partners about the build up of pressure pipes, the end customer needs and our high pressure pipe production process solutions with thermoset pipes. This knowledge sharing between the partners put us in the position to develop and to produce successfully high pressure glass fibre reinforced thermoplastic pipe demonstrators including a high pressure connection.

The results show that there are only a few developing steps more to go to finalise the high pressure demonstrator pipe and to reach a marketable end product. Using these results and finalising the end product by process adjustment and product certification, can have the potential socio-economical impact that pipe systems with critical liquids can be build with a higher safety for the environment than it is done today with steel pipes, this will result in a higher acceptance of official authorities regarding the approval procedures of critical pipe systems.

As for the dissemination activities, IPT represented all the 18 partners in the EU-research project on October 2013 to receive the JEC Americas Innovation award in the category process. The research group was awarded for the work in the development of an integrated process chain for the flexible and automated production of composite products in small and medium lot sizes.
Road mapping
Within FibreChain the first profound technology review and roadmap on thermoplastic prepregs technologies for cross industrial application has been performed by Fraunhofer IPT. The technologies, markets and products have been extracted, that have the highest potential now and in the near future. By executing the recommendations a short term ROI is ensured as well as sustainable competiveness. In detail one of the findings was to first invest in tape winding technologies to be able to produce pipes and pressure vessels especially for the oil and gas industry. The revenues should than be spend on the development of sensor integrated, shell-like thermoforming parts e.g. for automotive applications as this will be a huge future marked with a lot of revenue.

The study helped Fraunhofer IPT and the project partners to evaluate markets, products and technologies end to establish their individual and joint, sustainable research plans.

As a result of the dissemination focus, the oil & gas industry is now one of the major industrial customers of Fraunhofer IPT in the field of composites.

Also other research institutes have been inspired by the FibreChain study and already ordered additional, constitutive studies for further applications, materials and industries.

The FibreChain project had a huge and structural impact and Fraunhofer IPT, as the employment in the field of composite processing increased significantly as did the number and quality of technologies available for composite processing at IPT. Also IPT showed that it is capable to steer successfully an European large scale project on the development of whole composite project chain. By this the network and awareness significantly increased and solidified. As an effect, Fraunhofer IPT is known well known in field of composite technologies and made leap forward from supplier of special solution for niche applications to a contributor of holistic solutions for composite for major markets.

List of Websites:
www.fibrechain.eu www.fibrechain.de

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