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FP6 DINAMIT FINAL PUBLISHABLE ACTIVITY REPORT

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Abstract

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This report summarises the technical activities undertaken with the FP6 STREP DINAMIT Program during its 39 months duration.

The main achievements of works at the end of the program are underlined.

As a conclusion, comparisons are made, with references to the state of the art on TP technologies, at the beginning of the program,.

A final plan for using and disseminating the knowledge is presented.

Keywords

High Performance Thermoplastics, TPs Materials & Technologies, FP6 DINAMIT

Report circulation	**Project Manager :** Patrice LEFEBURE	**Scientific Director** Didier LANG
Abstract circulation		

(1) Or his « Head of operation », « Scientific Director » , « Scientific Advisor », by delegation.

Contract no. AST3-CT-2003-502831

DINAMIT

Development and INnovation for Advanced ManufacturIng of Thermoplastics

Instrument : SPECIFIC TARGETED RESEARCH
Thematic priority : AERONAUTIC AND SPACE - PRIORITY (4)

FINAL PUBLISHABLE ACTIVITY REPORT

Period covered : **From 2004/02/01 to 2007/04/30.**

Date of preparation :**May 2007**

Start date of the project: **2004, First of February** **duration**: **39 months**

Project **Coordinator Name** : **Patrice LEFEBURE**

Project **Coordinator Organisation Name** : **EADS France IW**

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1 PUBLISHABLE SUMMARY

1.1 OBJECTIVES OF THE PROGRAM

Today the High Performance thermoplastic composite parts are mainly used in aeronautical structures. Compared to thermoset resin systems, they have many advantages like impact behaviour, fire resistance, low moisture absorption, and welding capabilities.
Nevertheless, the material costs, and the global production costs remain generally high compared to thermoset composite technologies. They are furthermore generally restricted to simple geometry parts and limited dimensions, due to the current technological limitations.

The project final aim of the DINAMIT program is to foster the widespread use of thermoplastic high performance composites on aircraft or helicopter structures. To reach this final aim, the project will concentrate on the following objectives:

- Reduction of the prohibitive material costs.
- Reduction of the associated forming-consolidation costs
- Development of rapid, flexible, low cost processes for structure assembly
- Reduction of scraps.

The main innovations resulting from this 36-month project, which has been launched on the first February of 2004, will be in relation with the above-mentioned objectives:

- **The development of low cost high performance thermoplastic composite applicable to aeronautical structural components based on:**
  - Blend of thermoplastic structural matrix.
  - A newly developed structural resin: PEKK
  - Multiaxial thermoplastic fabrics

- **The development of new forming-consolidation processes based on:**
  - Assessment of a high speed automated lay up process used to the manufacture of thermoplastic double curvature structure parts into oven.
  - Improvement of the in-situ consolidation process for double curvature structural parts.
  - Assessment of a new vacuum diaphragm forming technique dedicated to the elaboration of large dimension structures with double curvature.
  - Assessment of a new low-pressure injection process for elaboration of high performance thermoplastic composite parts for substructures.
  - Improvement of Thermoplastics continuous forming and roll-forming technologies for substructure applications.

- **The development of new welding processes based on:**
  - Assessment of an in-situ welding process associated, with an in-situ consolidation process.
  - Feasibility study of Laser welding for assembly of high performance thermoplastic composites components.

- **The development of a cost optimisation tool which** will assess the developments of innovative TPs materials and processes

1.2 DINAMIT CONSORTIUM

The constitution of the consortium is diversified, with the presence of

- Aircrafts and helicopters manufacturers.
- Research institutes and university laboratories.
- Smes

Parti c.Role*	Part. no.	Participant name	Participant short name	Country	Date enter project	Date exit project**
CO	1	EADS Innovation Works	EADS IW	France	T0	T0+39
CR	2	AIRBUS FRANCE	A-F	France	T0	T0+39
CR	3	AIRBUS DEUTSCHLAND	A-D	Germany	T0	T0+39
CR	4	AIRBUS ESPANA	A-E	Spain	T0	T0+39
CR	5	AIRBUS United KIngdom	A-UK	United Kingdom	T0	T0+39
CR	6	Dassault Aviation	Dassault Aviation	France	T0	T0+39
CR	7	EUROCOPTER	ECF	France	T0	T0+30
CR	8	LTSM	LTSM	Greece	T0	T0+39
CR	9	CIDAUT	CIDAUT	Spain	T0	T0+39
CR	10	LPW BAYREUTH	LPW	Germany	T0	T0+24
CR	11	ACM Gmbh	ACM	Germany	T0	T0+27
CR	12	EIRE Composites Ltd	E.C	Ireland	T0	T0+39
CR	13	IVW Kaiserlautern	IVW	Germany	T0	T0+12

1.3 SUMMARISED DESCRIPTION OF WORKS

The works have been split in 6 technical workpackages for achievement of the objectives.

- New Materials
- New TPs Processes for forming - consolidation of skins
- New TPs Processes for forming - consolidation of substructures
- New Thermoplastics assembly Processes
- Validation of the developments
- Cost effective Analysis.

1.3.1 Development of new materials

New TP Blend resin specifications have been first established, with PEEK as the reference resin. Associated Blend UD tapes and fabrics specifications were also defined. Basically **a 20% reduction of mechanical or thermo-mechanical properties is accepted.**

A variety of blend material was formulated and characterized. Thermoplastic polymer suppliers like Victrex and manufacturers of semi-finished materials, like Porcher and Tenax, have been involved to guarantee from the very beginning an ideal interaction between the novel polymer and future fabric- and unidirectional materials or NCF. Basically, the new thermoplastic blends are characterized by following issues:

- Neat blend properties
- Resistance against aggressive media
- Mechanical performance in composite materials (unidirectional, fabric and NCF)

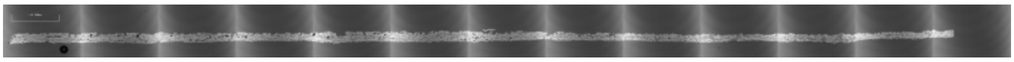
Starting point for the blend development was a basic blend of PEEK / PEI in 87/13 weight ratio. As third phase, PES is added. With higher PES content, brittleness of the blend is increasing, media resistance is decreasing, but also material costs can be lowered.

2 ternary blends 2002 HV 150 PEEK/PEI/PES (60/9/31) & 2005 LV 90 PEEK/PEI/PES (60/9/31) were definitively chosen for characterisations. The blend resin properties are mainly equivalent to PEEK on a mechanical point of view; it can be summarised by the following lines:

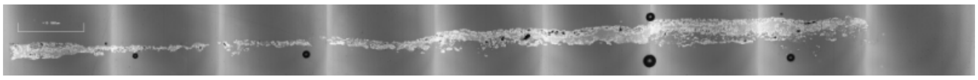
- ➢ High stiffness and strength, good media resistance, higher performance compared to PEEK at higher temperatures (180°)
- ➢ Generally, decreased toughness with respect to PEEK. The blends are more sensible to defects (cracks, voids, inclusions)

Difficulties were met, when manufacturing **UD tapes** (TOHO TENAX see fig. 1) due to big PEEK particles sizes:

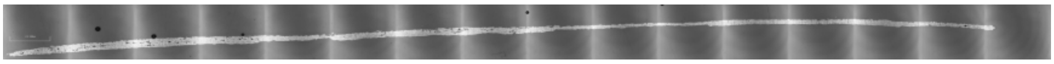
0613: Tenax HTS P-yarn / 2002 HV 45 mm (60-80 mm width)



0606 / 0607: Tenax HTS P-yarn / 2005 LV 100 µm (60-80 mm width)



Tenax HTS P-yarn / PEEK (60-80 mm width)



Gurit: AS4 / PEEK (12,7 mm width)

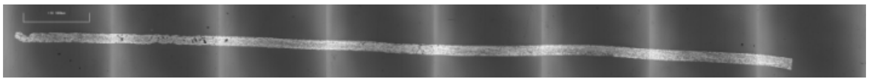


Fig1: micrographs of blend tapes compared to PEEK references (Airbus –D)

The ILLS and tensile tests, which were supplied on consolidated blend tapes coupons demonstrated close properties to the specifications. It remains nevertheless a poor quality of resin impregnation of the fibres, as showed with fractography analysis.

TP fabrics have been manufactured (PORCHER) from the 2 blends without particular problems. The impregnation has been made on a 5 satin weave already known on others composites with thermoplastic and thermoset resins.

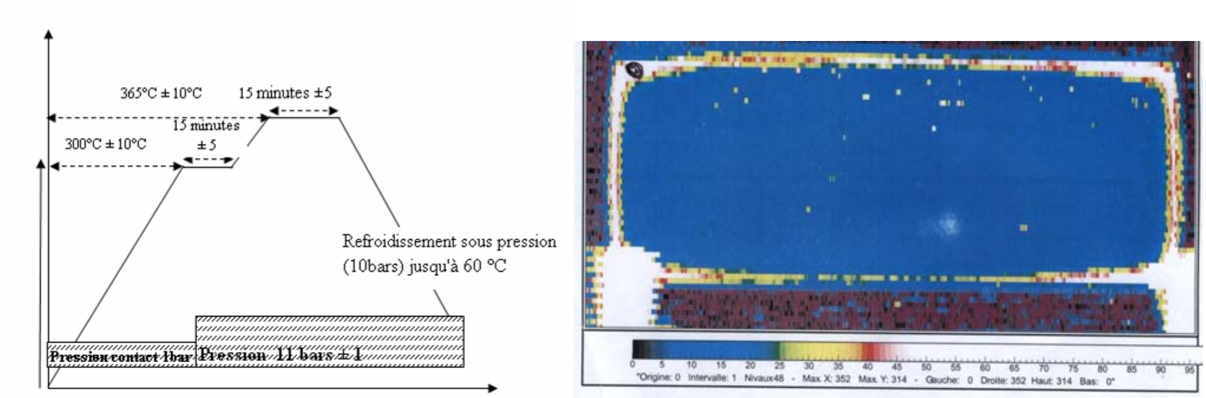


Fig2: consolidation of blend fabrics laminates (EUROCOPTER)

DSC, Tg and mechanical tests and thermo mechanical tests (bending and ILSS tests) demonstrate a good behaviour of TP blends products compared to the PEEK/C reference; in the tolerances which were defined by the specifications. It must be noticed also that the processing temperature did not decrease drastically near to 300°C as required, due to the high content of PEEK resin (fig. 2).

Different Multiaxial fabrics have been selected and tested (fig.3).

	SUPPLIER	DEFINITION
1 -	PORCHER (NCF from SAERTEX)	Peek powder on external NCF sides
2 -	SAERTEX (fibres from COMFIL)	Carbon/peek continuous commingled fibres
3 -	HEXCEL (fibres from SCHAPPES)	Carbon/peek cracked commingled fibres
4 -	HEXCEL	Peek fleece between each ply
5 -	HEXCEL	Peek powder on each dry ply (« Towflex »)

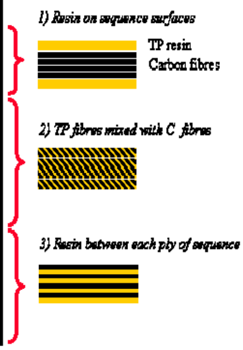


Fig3: different TP NCF presentations (Airbus-F)

As a main result from consolidation, formability and mechanical tests (i.e. plain Tensile, Open Hole Tensile, plain Compression, Open Hole Compression, Filled Hole Compression tests) The TOWFLEX NCF (HEXCEL) represents the best quality material; its drapability is lower than the other ones but its tensile properties are the better ones. For compressive behaviours optimising, commingled solutions seem today above (fig. 4).

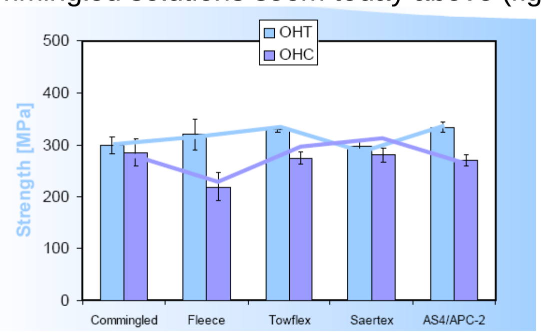


Fig4: mechanical results on TP NCF (LTSM+ Airbus-F)

Rheological tests and DSC have characterized PEKK, the blends and PPS matrix systems. The influence of temperatures on the rheological performance has been demonstrated in the frame of a complete analysis of the injection behaviour. The influence of oxidations effects has been highlighted on the 2 blends and PPS resins. From these analyses the choice of the FORTRON 205P4 PPS have been made by EADS IW, for development of a low-pressure injection process. An injection window has been thus defined, which seems very narrow.

A specific study of the influence of these oxidations effects on PPS resins at high temperature, on the consolidation capabilities of PPS/C laminates and on their related mechanical properties was set up.

Oxidation of the tapes during the forming-consolidation process induces mainly a large amount of porosity in the composite PPS/C parts. Therefore drastic decreasing mechanical properties are observed compared to references (fig. 5). It remains nevertheless that a small amount of oxidation may lead to a slight increase of tensile and compression properties, due probably to some cross-linking effects in the TP matrix.

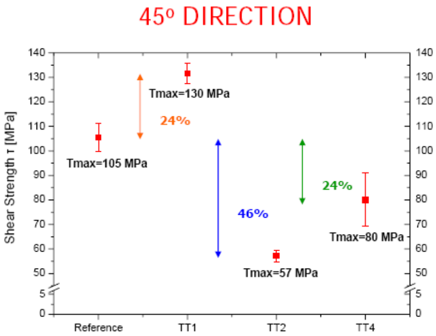


Fig5 : 45° tensile results_PPS/C laminates (EADS+ LTSM)

At last, It was finally demonstrated, from specific consolidation tests and plates deformations measurements after consolidation, that only very high cooling rates could induce drastic residual strains into PPS/C laminates, due probably to the cristallinnity gradients inside the part.

PolyEtherKetonKeton (PEKK) is a fairly new polymer for the use of thermoplastic composite prepregs. PEKK is promising to fill the material gap between cost of PPS and performance of PEEK. The Basic idea is to establish also PEKK materials, along with novel thermoplastics based on ternary blends, as a serious competitor to PEEK derivates. It is clear that cost is the driving force for these investigations – material cost is lowered vs. PEEK and the processing temperatures can also be fairly reduced by ca. 30 – 40°C.
Works on the comparison of mechanical data of consolidated PEKK/C panels with press- and autoclave processing have been done by Eire Composites.
The results show that:

- Tensile strength of press formed specimens, under all conditions, are slightly higher then Autoclave formed specimens. Both sets of results are higher than predicted.
- Compressive strength of both OHC and PC are roughly the same for press formed and autoclave formed under all conditions and thicknesses. Both sets of results are slightly higher than predicted
- CAI results for press were as expected. Autoclave results were higher then usual.
- In-plane shear results for the autoclave were slightly higher then the press results, both of which were as expected

Material Specifications for new PEEK or blend/C, 1-inch width tapes have been elaborated for automated Tape lay down processes applications, and submit to different Materials suppliers. GURIT was the only supplier, ready to answer to the request and to supply a new 90 PEEK/AS4 35%, 1-inch tape. The quality of the tape is good and In-Situ consolidation tests confirm a similar behaviour to the reference tape. (fig.6)

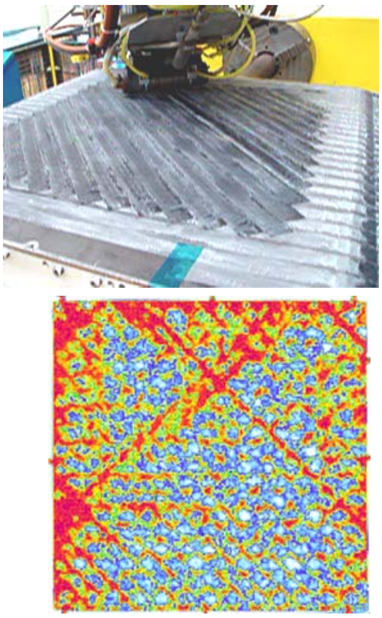


Fig 6 : ISC tests with new PEEK/C tape (Dassault Av.)

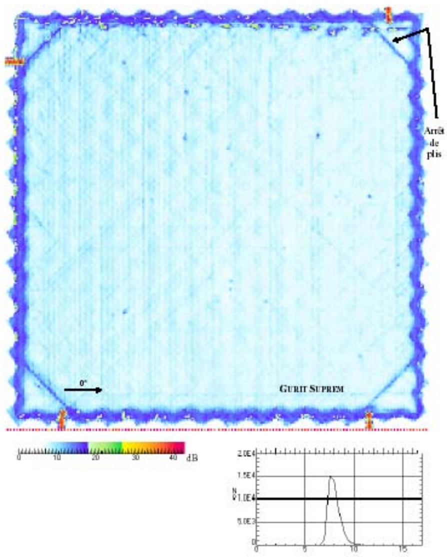


Fig 7 : new PEEK/C tape lay down + autoclave consolidation (Dassault Av.)

Other tests understanding high speed lay down of TP layers with post consolidation of the laminate into autoclave were set up (fig.7), which demonstrated the availability of this new PEEK/ C for automated lay down processes

1.3.2 *Development of new TP Processes for forming consolidation of skins*

The global objective was to develop innovative techniques for manufacture high performance double curvature panels focusing on the cost effective interests of the developments. Therefore it was quite natural to focus one part of the works on automated fibres placement technologies, such as demonstrated for thermoset composites. The other part was dedicated to the development of a specific enhanced diaphragm technique, understanding optimised heating system with an Infra red technology.

Automated TP tape placement techniques

The first problem to solve is the sticking problem of the first ply to a double curvature tool, because of the lack of TP tapes tack at room temperature. Two specific techniques have been developed within the DINAMIT program.

- The first technique is a vacuum technique. A specific tooling is used, understanding calibrated holes on surface in order to permit to have a good vacuum breathing. Therefore the first ply, which is manually deposed, is sticked during all the process on the tooling with the vacuum, created by a dedicated pump.

- A specific first ply (C/PEEK with PEI film) has been also used for automated deposition, coupled to a specific preparation of the tooling with a Peel ply impregnated with PEI spray (fig 8). The feasibility tests demonstrated that this technique was not available for low lay down speeds, such as used for In Situ consolidation processes, but was OK for high speed lay down processes with post consolidation into autoclave.

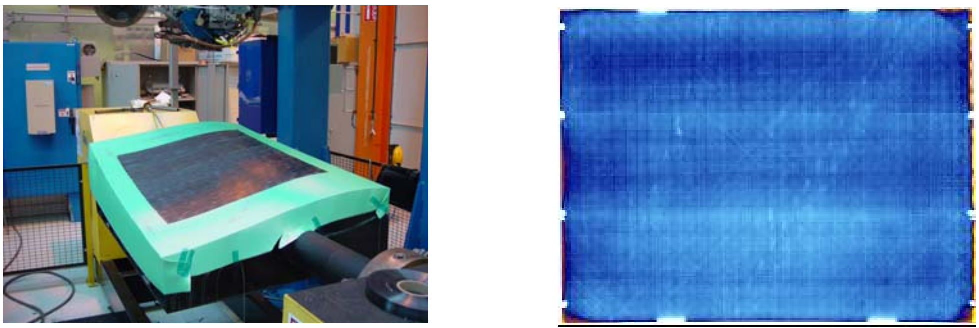


Fig 8: feasibility tests by Dassault Aviation with PEI surface preparation technique

A serial of automated lay down tests (fig. 9 & 10) have been fully set up for determining the optimum high speed lay down process parameters (speed, temperatures, applied force), which must be used for consolidation of a TP double curvature nose fuselage panel into oven. A Process window has been thus determined after health analysis of representative consolidated patches, by mean of CSCAN analysis.

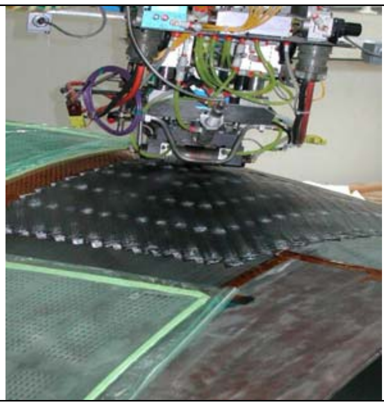


Fig9: EADS IW lay down test	**Fig 10: EADS IW feasibility DC APC2/AS4patch**

As main conclusions, it has been estimated that it was possible to consolidate only under vacuum double curvature TP panels, which were automated lay down using high tape deposition speeds, compared to ISC process.

All the feasibility tests nevertheless demonstrated that the process quality is drastically affected by the material quality of the TP tape.

The effects of the consolidation force and process velocity parameters on tape placement process were investigated by using a special developed test rig, allowing performing tests in many different configurations. The advantage of the hot gas gun compared to the flame and in particular to the infrared spot heater has been furthermore observed (fig. 11).

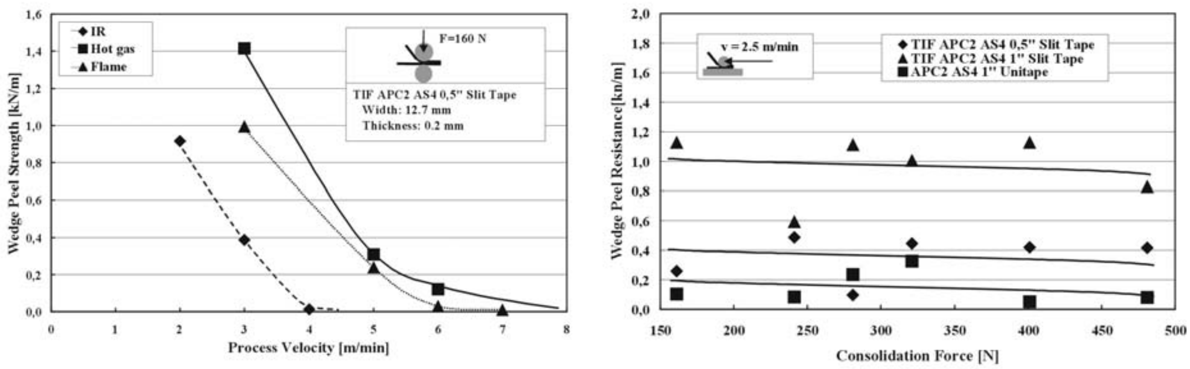


Fig. 11: influence of process parameters (IVW Kaiserslautern)

New diaphragm process & associated Infrared heating

This axis of work was split in 2 main associated blocks: The first one dedicated to the development of an innovative diaphragm forming technique, and the second axis focused on a modelling Infra red thermal approach for optimising the heating of the mould and blanket during the process.

The objective was to evaluate the ability to form and consolidate deep curvature TPs parts.
A specific mould has been designed and manufactured. A new high temperature silicone membrane was designed and manufactured for this diaphragm technique & a specific 4 satin 380g/m2 PPS/C fabrics (SCHAPPE) was used (fig 12).

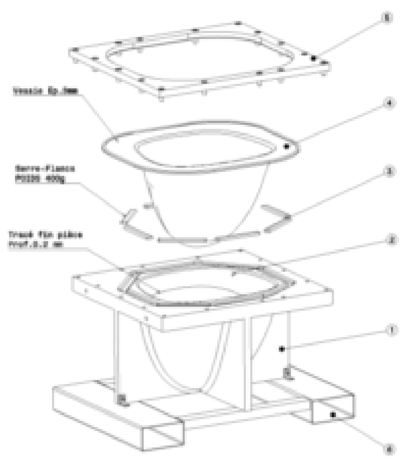


Fig. 12 : Eurocopter diaphragm technique scheme

Fig. 13 : PPS/C Canopy _ Eurocopter feasiblity part

The process window has been established (time temperature, vacuum, pressure) and the part (reduced size Canopy) has been manufactured (fig. 13). The quality analysis, which was performed, demonstrated the acceptable quality of the part in term of health and geometry.

An analytical IR heating model has been established for modelling this diaphragm process. Thermal and mechanical analysis s, as well as a combined thermo-mechanical analysis was performed for optimising the optimal mould temperatures (fig. 14).

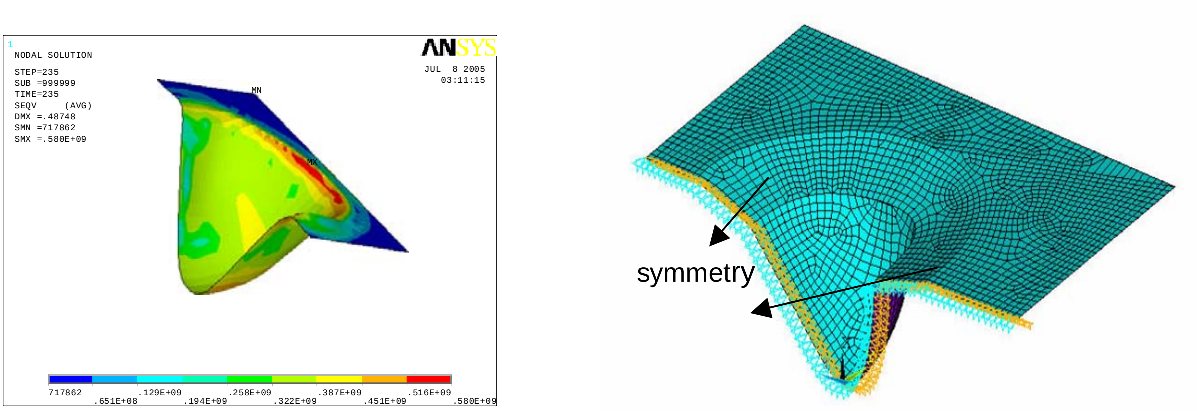


Fig 14: IR heating and forming model (LTSM)

The thermal analysis has been performed by varying the process parameters (Power of IR lamp, IR lamp pitch, distance between IR lamp and plate, number of IR lamps) and the thickness of the plate (fig. 15). An optimal solution has been presented

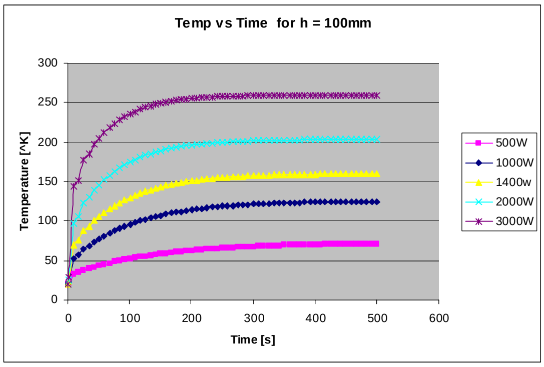


Fig. 15: Influence of the Lamp Power on the heating time.(LTSM)

1.3.3 *Development of new TP Processes for forming consolidation of substructures*

The developments concerning TP techniques for substructures were axed on 2 main directions. The first one is more innovative, with works on a direct low-pressure injection process to be competitive with thermoset RTM process on the same field of applications. The second one is more focused on a cost effective forming consolidation process, by the enhancement of continuous forming consolidation & roll-forming process of high Performance double curvature Thermoplastics components.

A literature review has been first established about the different reference industrial techniques, which are used today for manufacture of High Performance Thermoplastics substructures.

A specific injection technique has been developed for manufacture of TPs substructures. The first interest is to be able to manufacture complex geometry composite components, which could be directly available for simple welding to a high Performance Thermoplastics skin. The principle is based on the direct injection of PPS resin into a Carbon preform (Satin 5 fabrics) at low pressures, compared to traditional TP injection techniques. The challenge can be summarised by the combination of the following constrains:

- Injection of very high viscosity materials (near 100 Pa.s)
- High temperatures of process (more than 300°C).
- Limited pressures (max 20 bars).

A specific machine and a dedicated tooling were used for feasibility tests, by mean of injection of PPS/C laminates (4 mm thick) with a tooling, positioned under a heated plates hydraulic press (fig 16).
Severe problems of materials quality, the existence of a narrow process window due to PPS oxidation during the extrusion step of the pellets, at last incidents on the new injection machine dedicated to the process, troubled the completion of the tests. Main efforts were therefore dedicated to preparation works, instead of pure injection tests.
A PPS/C laminate has finally been successfully fully Injected (fig. 17); after elaboration of the extrusion windows for PPs pellets, and after a few feasibility injection trials. It was observed good fibre-matrix cohesion after consolidation, even if a low level of porosity (< 3%) remains inside the part. The presence of microcracks is very limited, although it is generally considered as the main drastic problem for PPS/C structures.

Fig 16 : EADS IW injection devices

Fig. 17 : PPS/C injected laminate _EADS IW

This can be considered as a very promising result, taking care of the very innovative aspect of the technique. It should open consequently the door to further specific developments for manufacturing High Performance thermoplastics frames or stingers and also should lead to work on a more scientist point of view, on the deep understanding of the phenomena, which occur during the process.

Continuous compression moulding technique was an other important axis of development. The principle of this multi step process is the following:

- The semi finished thermoplastic material is heated in a mould, pressed and cooled. After pressing, the press opens and the material is pulled one step further. In the first step of the process at the material inlet, the material is introduced into a mould and preformed. It is then brought up to processing temperature in a preheating zone and pressed in the compression zone. The cooling system integrated in the mould cools the material to room temperature. The feed system comprises a hydraulic clamp and actuates a feed cylinder.

The continuous forming machine is now adapted and the process is optimised for the fabrication of TP 3D contoured profiles. This has been done from the evaluation of the results obtained from flat tapes manufacturing to complex shape parts with different TP materials. On the basis of the evaluation results and Dassault design of the shapes, a tooling for 3D shaped stringers was designed and manufactured by ACM. APC2/AS4 Z stringers were continuous formed and supplied for manufacture of the APC2/AS4 panel understanding a PEI welding to the skin of these stiffeners.

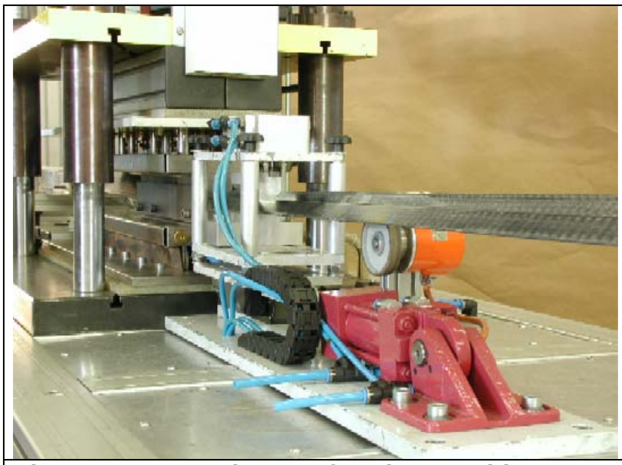
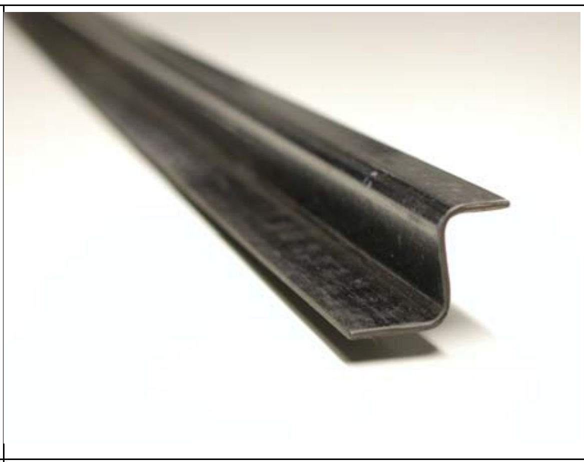
	

Fig 18: ACM continuous forming machine	**Fig 19: APC2/AS4 Z contoured stringers (ACM)**

An existing Thermoset Roll forming machine has been transformed for high performance TPs applications, with addition of IR lamps systems, adapted insulation systems and heat resistance rollers, in order to be able to fully preheat TP blankets up to 380°C. The machine must be available for manufacturing 2m length TPs parts with forming speeds from 1 to 4 m/min.

Unfortunately the developments are not today completed (No roll forming feasibility tests) because of the difficulties, which were met during the project in order to develop this specific TP forming-consolidation machine.

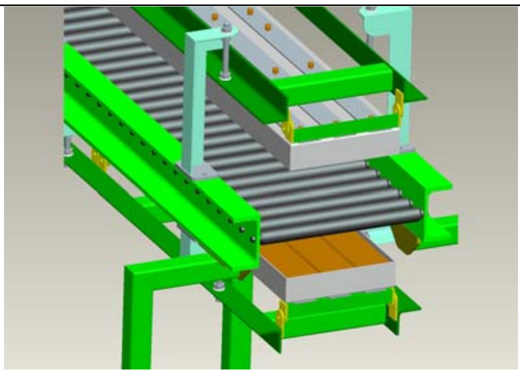


Fig 20: TP roll forming device design (A-UK)	**Fig 21: TP roll forming machine (A-UK)**

1.3.4 New Thermoplastics Assembly Processes

The works have been structured in two main blocks based on the main technological approaches under investigation. The first block of tasks has been dedicated to the investigation of laser-based technologies for joining of thermoplastic composites.

- This block encompassed two main applications: on one hand, the feasibility of laser for transmission welding of thermoplastic laminates has been investigated. On the other hand, the use of laser for the surface preparation of both thermoset and thermoplastic laminates prior to bonding with adhesive film has been studied.
- The second block has been dedicated to investigate the utilisation of a cost-efficient welding technique based on the application of a poly-ether-imide (PEI) film for the assembly of high performance laminates based on poly-ether-ether-ketone (PEEK).

Laser welding feasibility

Laser welding present a series of inherent advantages over other welding techniques used in the past for joining thermoplastic composites: controllability of process parameters, no need to introduce foreign materials within the parent laminates to be welded, possibility to operate remotely from the laser sources via fibre optics, ability to concentrate heat only where required, thus reducing the heat affected zone, among others. Prior to DINAMIT, very little work had been reported on the use of laser transmission for the welding of fibre reinforced thermoplastic composites. With this approach, the laser is focused on the interface between a top laminate that is partially transparent or translucent to the laser radiation of a determined wavelength and a bottom laminate, which is mostly absorbent to this radiation. The material at the interface melts down and the welding takes place (see Figure 1). Positive results on certain neat thermoplastic material combinations motivated us to extend the approach to study the applicability of this technology to reinforced materials.

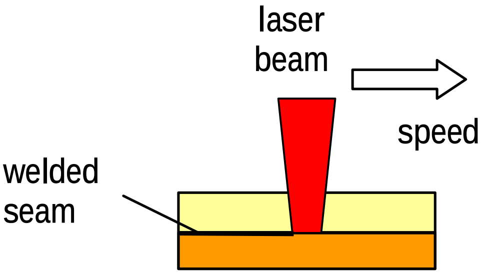


Figure 22:. Typical transmission welding arrangement (CIDAUT +Airbus –E)

The feasibility of laser welding of a series of material combinations, looking at high performance thermoplastic resin systems such as poly-ether-imide (PEI), poly-phenylene-

sulphide (PPS), poly-ether-ether-ketone (PEEK) and poly-ether-ketone-ketone (PEKK) together with continuous glass and carbon fibre reinforcement both in unidirectional tape and woven fabric presentations has been investigated using different laser sources (CO_2, Nd:YAG, diode).
In terms of glass fibre reinforced thermoplastics, it has been found that satisfactory results in terms of laser weldability can be achieved with PEI only when a diode laser source (940nm wavelength) is used, since this material is partially transparent to the laser radiation at this wavelength. In order to achieve good quality welds, an absorbent material has to be placed at the interface: black paint on one of the parent laminates and an interleaved carbon-black filled PEI film have been tested successfully. When the bottom laminate is carbon fibre reinforced, the PEI/glass laminate can be welded without the need for this concentrator of radiation. This has been demonstrated when welding PEI/glass to a PEKK/carbon laminate. In contrast, PPS/glass has proved to be absorbent to laser radiation in all wavelengths tested (Nd:YAG and diode) and therefore, polymer degradation and resin burn-off occurs at the surface of incidence of laser before welding can be achieved.

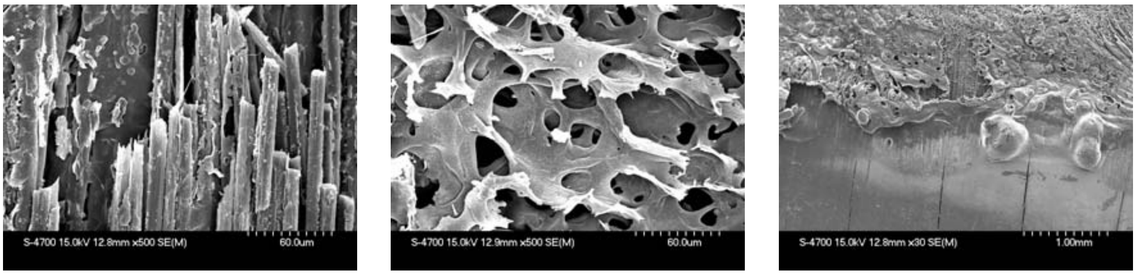


Fig. 23:. Typical damage morphology of CF/PPS at the surface impacted by the laser (Nd:YAG)_CIDAUT

Carbon fibre reinforced laminates have proved much harder to weld using laser transmission welding due to the inherently absorbent nature of the carbon fibre. Most of the laser energy gets absorbed at the surface directly impinged by the laser, which leads to overheating and subsequent resin and fibre degradation (see Figure 2). Only when the top laminate is very thin (of the order of 0,5 mm or less) and the welding process parameters are optimised (laser power, velocity of the head), effective welds can be achieved. This has been demonstrated on carbon fibre fabric reinforced PPS laminates welded with a Nd:YAG source. In all cases some amount of degradation of the top laminate occurs, but sufficient weld performance can be obtained as has been observed on coupon specimens in single-lap shear tests (see Figure 3). Best results are obtained when using less power at lower processing velocity.

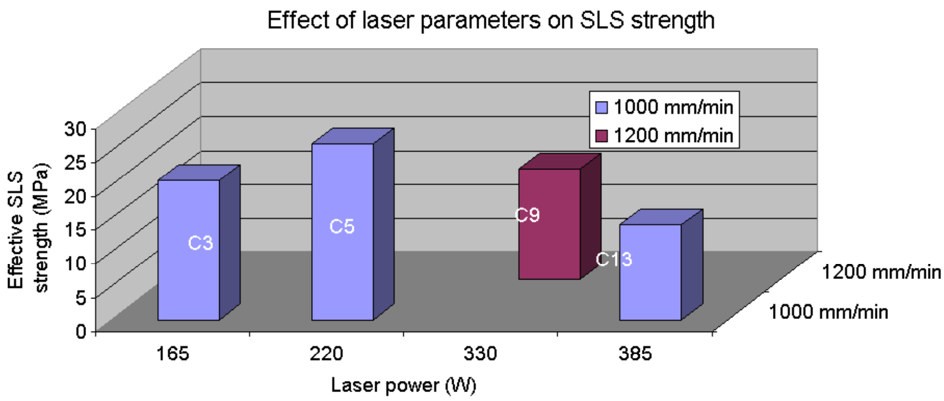


Figure 24: Single lap shear test results on welded carbon fabric/PPS specimens (0,5mm thickness) as a function of laser (Nd:YAG) parameters (AIRBUS –E)

Feasibility of laser welding for carbon reinforced thermoplastics is therefore restricted to very low thicknesses, which makes it not an efficient approach for welding typical airframe parts. However, laser could still constitute a suitable candidate as heat source for automated in-situ consolidation processes for the manufacturing of carbon fibre reinforced laminated parts, since typical thicknesses involved range within 1 to 3 tenths of a mm. Currently, hot-gas torches are the state of the art heat sources, which can lead to potential surface degradation if the fuel/air mix is not well metered and has some limitations regarding spatial controllability. Preliminary trials have been made on carbon fibre/PEEK unidirectional tapes within the framework of this DINAMIT work package. Despite the fact that an appropriate tooling was not available to simulate realistic processing conditions, satisfactory welds were realised using CO_2 and Nd:YAG lasers. Although no tests were performed with a diode laser source, there are no reasons to think it could not be a suitable source for this application. These preliminary results open an interesting route for the application of laser to the automated processing of carbon-reinforced thermoplastics, which should be further pursued.

Laser surface preparation prior to bonding

Manual sanding is the current practise for surface preparation prior to adhesive bonding of composite parts in the aerospace sector, which is clearly not an attractive approach from the industrial point of view and therefore, suitable alternatives with a potential for automation are eagerly sought after by the industry. Within the framework of DINAMIT, an extensive investigation has been carried out on the application of different laser sources (YAG and diode) for the surface activation of both thermoplastic and thermoset composite laminates prior to bonding with a thermoset adhesive film.

All tested laser sources have proved to be very aggressive on the surface of thermoset composite laminates. Carbon fibre and hybrid glass-carbon fibre reinforced laminates with 180ºC and 150ºC-cure epoxy resins have been tested and all laser parameter combinations led to severe degradation of the matrix and the fibres on the surface of the material, which translated into poor performance of the ulterior bonded joints. This degradation is again caused by the highly absorbent character of carbon fibres, which leads to overheating of the surrounding matrix. Evidences of less degradation have been observed in the areas surrounding glass fibres in the laminates manufactured with hybrid glass/carbon prepregs as a consequence of the partial transparency of the glass fibres to the laser radiation.
In turn, when lasers were used to treat carbon reinforced PEEK laminates, much more promising results were obtained. The higher temperature performance of this semi-crystalline thermoplastic resin is responsible for the lower levels of matrix degradation at the surface (although still present) and the higher performance in terms of shear strength of the adhesively bonded joints (see Figure 4). Test results evidenced that good results (higher levels of shear strength than those measured in specimens prepared by manual sanding) can be obtained with both laser sources tested (i.e.: YAG and diode), although diode laser appears to be more robust and less sensitive to changes in process parameters.

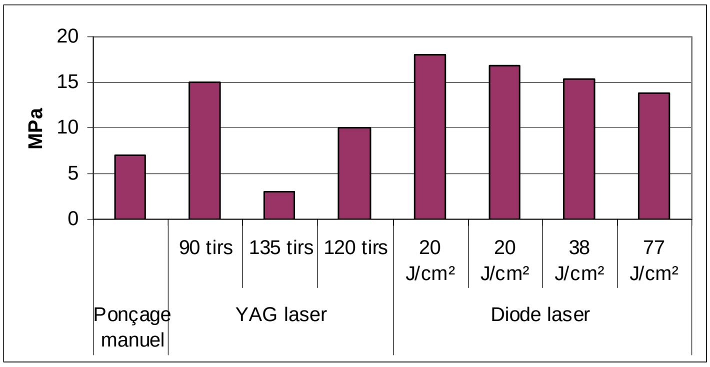


Fig.25: Single lap shear results on PEEK/PEEK adhesive joints bonded after manual sanding, YAG and diode laser surface preparation (EUROCOPTER)

As a result of this investigation, laser cannot be considered a suitable surface preparation approach for thermoset composites (at least for typical 180ºC cure resin grades) but it can certainly be deemed a promising technology, in particular using diode sources, for application on carbon fibre/PEEK laminates.

Cost efficient PEI welding process

The elevated processing temperature of PEEK based composites (about 400ºC) makes the welding of parts made with this material very costly, in terms of energy consumption (autoclave) and required ancillary materials with high temperature capabilities. A thorough investigation in a welding process has been carried out that uses PEI film at the interface of the carbon/PEEK parts, which substantially reduces the temperature required to perform the welding (300ºC). In addition, and also within the framework of this task, the use of a carbon foam tooling and a silicone membrane has been evaluated as innovative and efficient (reusable) ancillary materials for this process. The successful welding of z-shaped stiffeners to a flat skin has been used to demonstrate the feasibility of this technique (see Figure 26).

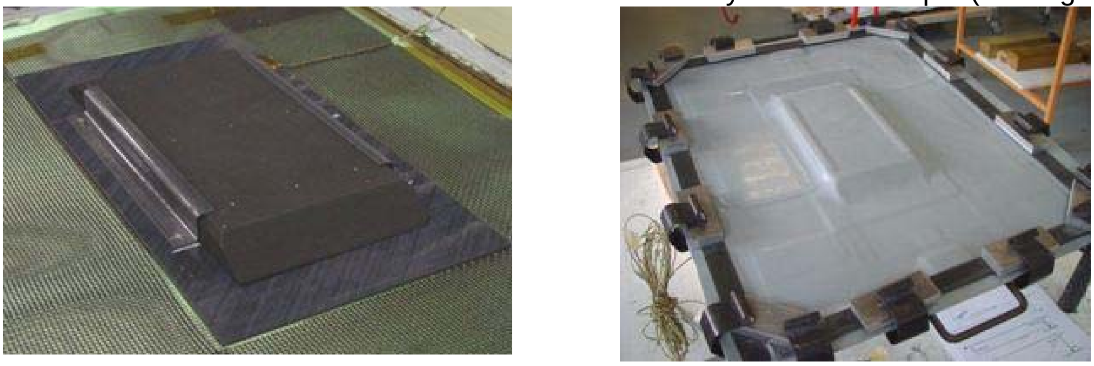


Fig. 26: Dassault Av._ Carbon foam blocks used as tool to hold stiffeners in place (left). Silicone membrane used to ensure good pressure distribution (right).

The mechanical performance of the welded joints using this technique has been evaluated at coupon level in terms of single lap shear strength. Results have shown that, despite the fact that the strength of specimens welded with PEI film is lower than that of a homogeneous PEEK/PEEK co-consolidated joint (due to the higher performance of PEEK resin when compared to PEI), this strength is still significantly higher than that of a typical adhesively bonded joint, which should be the actual baseline to compare with (see Figure 27).

It has also been shown that the lap shear strength is not overly sensitive to the number of PEI films used to perform the weld or the relative orientation of the carbon/PEEK plies at the interface. This trend has also been confirmed after carrying out pull-out tests on specimens cut out from a stiffened panel with stiffeners welded using the technique and ancillary materials developed within this work package. This demonstrates the potential of this technology to produce reliable and robust joints.

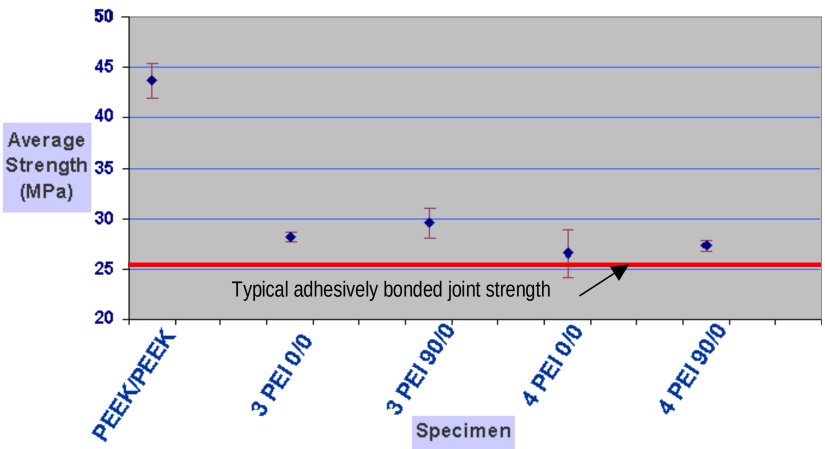


Fig 27: Shear results on welded joints (Airbus E +Dassault Av.)

1.3.5 Validation of the Developments

The validation works with manufacture of representative parts mainly concerned the innovative automated TP tape placement techniques, the use of new materials and the cost efficient PEI welding technique.

<u>Manufacture of a representative Airbus Nose fuselage panel</u>

An APC2/AS4-34%, CYTEC, double curvature skin panel was designed and sized by Airbus France, which is representative of an A320 nose fuselage geometry difficulties (reduced sizes but representative curvatures).

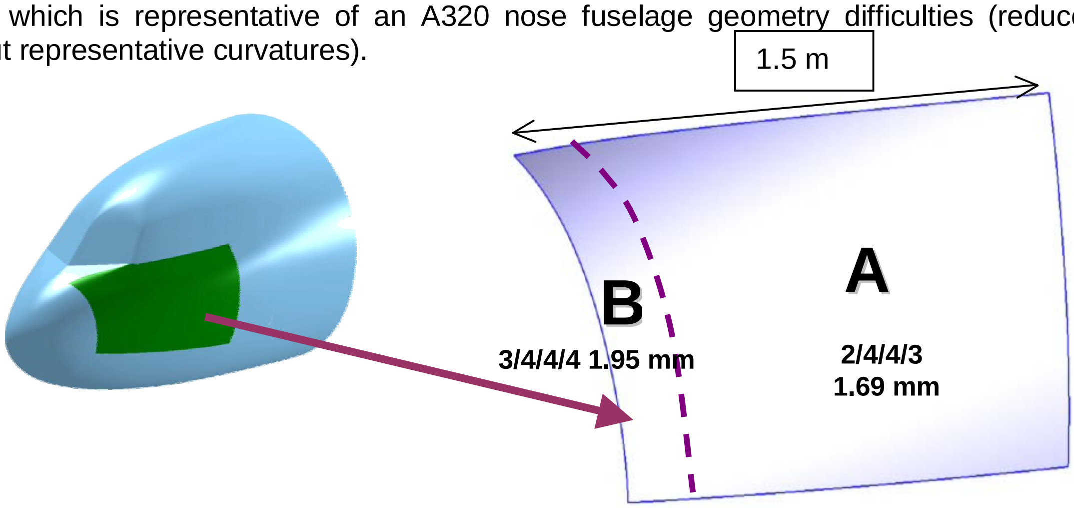


Fig 28 : Double curvature fuselage panel design (Airbus –F)

Geometry Inputs have been provided for programming the automated process & manufacture the part by EADS, with the previously developed high speed lay down technique, which is coupled to a post consolidation under minimal pressures (0.5 B max).
This has been successfully completed (see fig. 29) with the manufacture of 2 double curvature APC2/AS4 panels (13 +2 plies thick), using WP2 development results.
Laser ultrasonic analysis and micrographs validated the works.

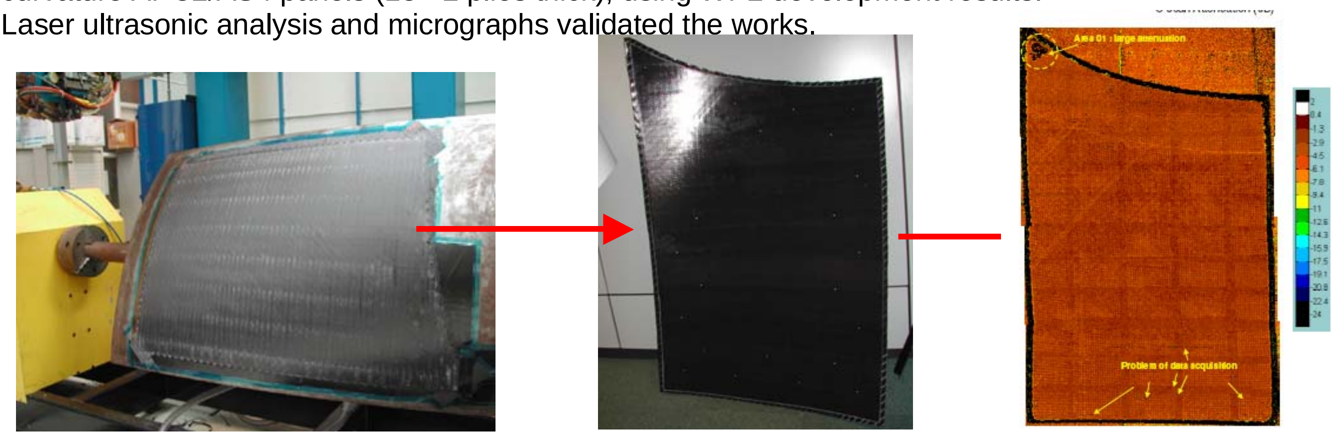


Fig 29:manufacture of double curvature APC2/A4 panels by EADS IW

As a conclusion It has been proven that the vacuum technology is an available technique for sticking the first TP ply to the tooling and that high speed automated TP tape placement coupled to post consolidation under vacuum could be a cost efficient solution for manufacture of aerospace composite panels.

<u>Manufacture of a representative falcon jet fuselage panel</u>

After designing & sizing the targeted TP landing gear door, it appeared to Dassault Av. that this validation part was not adapted to In situ consolidation processes. Therefore reorientation of works occurred; the validation part is a Z stiffened double curvature APC2/AS4 panel (flacon jet fuselage representative), which had to be manufactured with high speed lay down technique, new first ply sticking technique with PEI spray, autoclave consolidation (5 bars) and specific PEI welding technique for stiffeners assembly to the consolidated skin, as developed into WP2 and WP4. A dedicated tooling was designed and manufactured. The stiffeners were continuous-formed with the technique developed within DINAMIT, as soon mentioned.

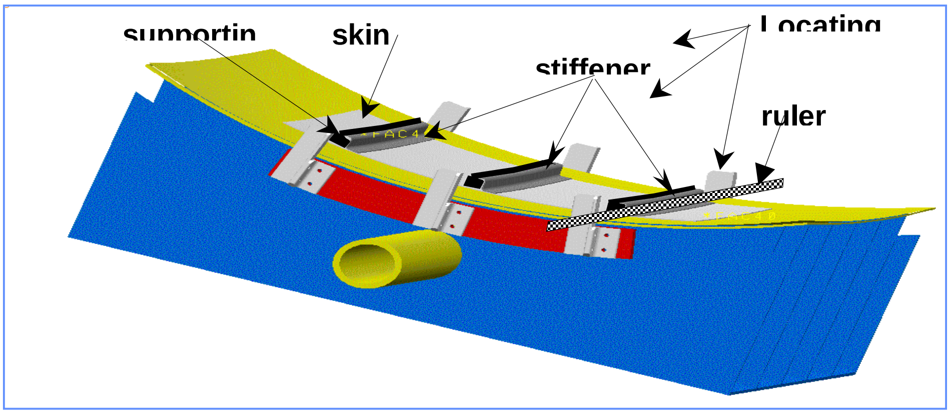


Fig 30: Dassault Av. Stiffened Panel Consolidation scheme

A 10 QI plies stiffened ACP2/AS4 panel has been successfully manufactured, which demonstrates the availability of the developments.

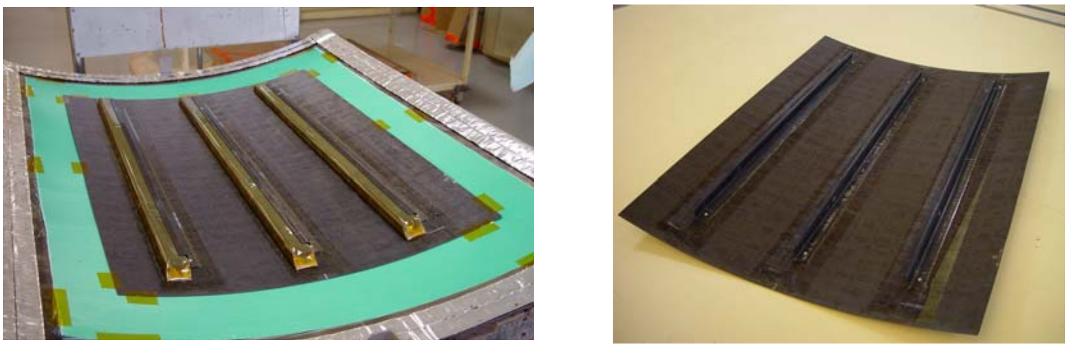


Fig 31: APC2/A4 panel stiffened with PEI welding of stiffeners to skin

__PEKK/AS4 rib manufacture__

A s**PEKK/AS4 rib** with welded TP roll-formed stiffener has been designed (fig. 32). The materials study results suggested that press forming gave higher mechanical properties than autoclave forming. Therefore it was decided to manufacture the rib using the former method. A specific mould has been designed and manufacture for press forming manufacture. The rib has been thus consolidated by Eire Composites according to the processing conditions, used for PEKK/C laminates evaluations (fig. 33).

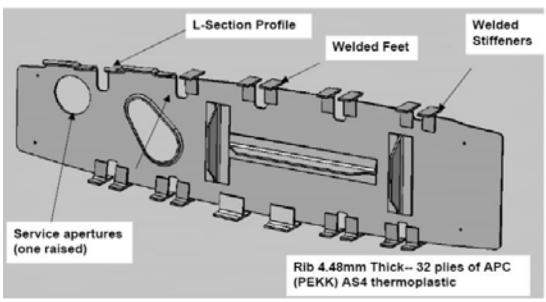


Fig 32: stiffened PEKK/A4 rib design (Airbus UK)

Fig 33: consolidated PEEK/AS4 rib & feet- Eire Composites

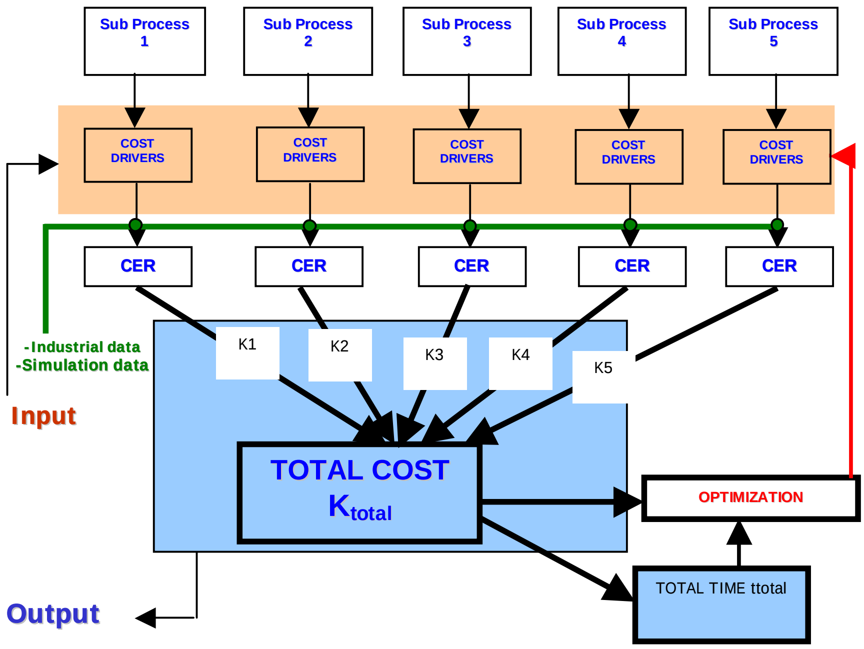
The feet for the rib were autoclave manufactured using back-to-back L-sections. Once de moulded, two L-sections were placed back-to-back and were bonded together using the adhesive 3M 9232 B/A.
Unfortunately the difficulties of development of the TP roll-forming technology did not permit the manufacture of the stiffeners and made this demonstration partially achieved.

Airbus France has designed a specific TP RTM frame to be manufactured with the specific thermoplastic injection technique developed by EAD IW. It was nevertheless decided at the end of the specific process developments for substructures, to reorient the injection validation works to the continuation of these developments. Therefore there are no injected TP PPS/C parts for validation of the developments.

1.3.6 Cost effective analysis

Ten (10) processes developed in the frame of DINAMIT project have been cost analyzed using the Activity Based Costing method. The steps of the Cost Analysis are listed below:

- Division of the process into sub-processes placed each one in separate excel sheet
- Introduction of the name of each sub-process and the derived Cost Estimation Relationship (CER)
- Calculation of the sub-process cost simultaneously with the introduction of Cost drivers value
- Division of the cost drivers to part data, process data and cost data
- Graphs extraction regarding sub-process Cost versus cost drivers variation
- Summation of the process cost (Ktotal) and of the process time (total)



- Where empirical (experimental) data was available, regression analysis was used in order to create accurate and realistic cost estimation relationships (CERs).
- Where empirical data was not available, theoretical analysis of the critical sub-processes was used in order to calculate the required data, which in turn was used to create the cost estimation relationships (CERs).
- Where different versions of the same process were existed, a different analysis was performed for each version for comparison reasons.

The respective version of the already developed cost analysis tool was created, Table 37, figure 38.

Part Data	*PAA* [m^2]	Part area (mold side)
	WP [kg]	Weight of part
	NPL [/]	Number of plies
	PAP [m]	Perimeter of part
	THPL[m]	Thickness of each ply
	APL[m^2]	Area of each ply
	cmp	Complexity
	PPA[m^2]	Part projected area (in contact with the mold)
	ρ[kgr/m^3]	Prepreg mass density
Process Data	*Ncl* [/]	Number of clamps
	NH [/]	Number of heating elements
	D [m]	Distance between the material and the lamps
	Nd [/]	Number of diaphragms
	P_L [W]	Power of each lamp
	Npc[/]	Number of pieces produced per year
	Lf[years]	Estimated life of equipment
	Nm[/]	Number of maintenances
Cost Data	k_{pr} (euro/kgr)	Cost of the prepreg per kgr
	k_d (Euro/m^2)	Cost of the diaphragm per m^2
	k_a (Euro/kgr)	Cost of the releasing agent per kgr
	k_w (euro/hour)	Cost of the specialized worker per hour
	k_{inf} (euro/hour)	Cost of one infrared lamp switched on per hour
	K_{vac} (euro)	Vacuum pump cost
	Equipment cost	
	Maintenance cost	

Table 37 Diaphragm Forming
Part, Process and Cost Data (LTSM)

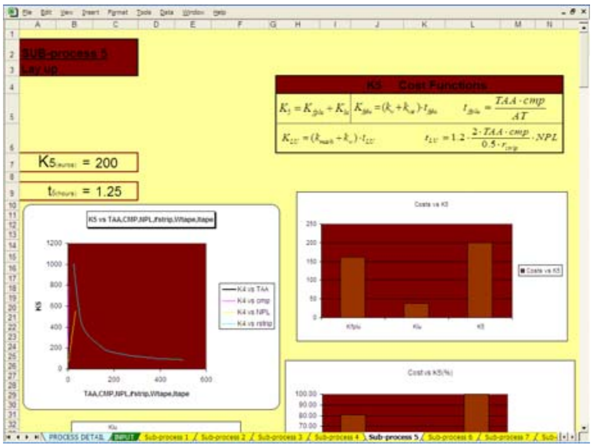


Fig 38: High Speed Lay-Up process cost analysis, sub-process 5 cost estimation (LTSM)

Each cost analysis tool was sent to the respective partner (excel file) for analysis before optimizations.

- The above cost analyzed processes were optimized in terms of cost and process parameters using the new cost analysis software LCAT which main characteristics are the following:

Cost Estimation Tool main Characteristics

- Easy accessibility by the user
- Friendly interface
- Fully parametric

- Divides the process into sub-processes
- Extracting graphs
- It can be modified any time

- Optimal set of process parameters with regard to quality and cost were created for each analyzed process using the LCAT, e.g. *table 39.*

Process Data	*Ncl* [/]	10
	NH [/]	100
	D [m]	0.05
	Nd [/]	1
	P_L [W]	800
	Npc[/]	200
	Lf[years]	15
	Nm[/]	600

Table 39: Optimal DF process parameter combination (LTSM)

1.4 CONCLUSION

We can now pull out the main conclusions on the technological advancements which are brought by the DINAMIT program, compared to the initial states of the art of each concerned Thermoplastics technologies.

New TP Materials

Referred to the structural PEEK & PPS based Composites, which are the references today for aeronautical applications, we proposed some interesting solutions.

- **2 New ternary blends resin and associated prepregs** are proposed.
  - Both blends showed some minor deviation in its properties. All results were in the once specified range of the PEEK baseline and the extended acceptance range of an allowed property reduction of –20% vs. PEEK.
  - The resulting composite panels had properties that were comparable in some cases to those of commercially available PEEK composites.
  - For its cheaper price: decreasing of 30% on the cost of blend can be translated into some percentage (10 to 20 %) on the prepreg.
  - According cost decreased, some applications where chemical and stress resistances are needed, blends are a good compromise to PPS (lower temperature service and impact resistance) and to PEEK (best performance but high costs)
  - In cases of speeding up the compaction cycle, the lower cristallinnity ratio can help to improve the feasibility of faster processing while maintaining the quality of laminate.

- **PEKK based prepregs** seem to be also an acceptable solution for TP substructures manufacture, to be confirmed by further structural mechanical tests.

- The evaluation of **new TP multiaxial fabrics** gave promising results, on their potentiality for cost efficient use on the manufacture of TPs fuselage aircraft skins. Further works are needed nevertheless to optimise

- **A new 1-inch width PEEK/AS4 tape** seems now available for automated TP tape deposition applications.

- We confirm at last the **difficulties to use PPS resin based products** due to the narrow material process windows, induced by the drastic evolution of the resin in the melt state during the process.

New TP Processes for skins.

- The DINAMIT program proposed 2 **innovative solutions to** answer to the previously existing **problem of first ply sticking** to a curved tooling. The first one is based a vacuum technology, the second one is based on use of specific material with PEI coating.
- Compared to the existing In Situ Consolidation process (slow tape deposition rate and today considered as a insufficient reliable technique), one of the main result of the program is to propose a **cost efficient** parallel route, which is based on **high speed TP tape deposition step coupled to consolidation into oven** of the panel.
- An **innovative diaphragm technique** using a specific elastomer membrane allowed to manufacture deep curvature Thermoplastics parts.

New TP Processes for substructures.

- An **innovative low pressure TP direct injection technique** has been developed. First promising results allow thinking that it could be an interesting route for manufacturing complex geometry substructures (such as fuselage frames or fittings), which would be directly suitable for cost effective assembly to Thermoplastics skins.
- A **continuous-forming process** is available now for contoured stiffeners manufacturing.

New TP assembly processes

- A complete Laser welding feasibility study permit to draw the conclusion that **the Laser techniques are not really suitable for aeronautical applications**, because they are restricted to very thin High Performance Thermoplastic composite part. Applications to automated tape placement may nevertheless be imagined.
- **Laser technologies** seem interesting as a technology **for surface preparation** before TPs parts welding, compared to the actual manual sanding.
- New silicon membrane and a specific carbon Foam have been validated for welding PEE/C stiffeners to a PEEK/C carbon skin with PEI film at the interface of the components.

Cost effective analysis

- A **specific tool is now available** and must allow to see rapidly the most influent parameters of the process on the cost of the under development techniques.

2 FINAL PLAN FOR USING AND DISSEMINATING THE KNOWLEDGE

2.1 EXPLOITATION TABLE

The hereafter table summarises the exploitation which is foreseen concerning the DINAMIT results.

Exploitable Knowledge (description)	**Exploitable product(s) or measure(s)**	**Sector(s) of application**	**Timetable for commercial use**	**Patents** or other IPR protection	**Owner** & Other Partner(s)involved
Vacuum technique for first TP ply deposition	Process Principle	1. Aerospace. 2. Automotive	Not applicable today	Extension of an existing protection	**EADS/CCR (owner)** + A-F
Development of new Multiaxial Fabrics with TP resin	Materials samples	Aeronautical Primary or secondary aircraft structures (fuselage application)	2007	To be considered	**Suppliers** selected by **A-F**: • Hexcel, • Saertex, • Porcher, • Schappes, • Comfils
First thermoplastic ply deposition technic for complex shape part.	Manufacturing process	1.aeronautic industry (aircraft structures) 2.oil and gas industry 3.cars, sport and leisure industry	2006 2007	A process patent could be planned for 2005,2006	**Dassault-Aviation**
Heat transfer analysis	Process model	Thermoplastics production industries		To be considered	**LTSM**
New thermoplastic resin for CFRP	Blend materials (PEEK-PEI-PES Blends)	1. Aeronautical 2. Automotive 3. High perfomance polymers in technical parts	2009-2012	A specific materials patent additional to existing patent could be discussed.	**Victrex (owner)** **LPW**
Continuous compression moulding technique	Technique to produce profiles like stringers for aircrafts in continuous way	1. Aircraft 2. Industrial 3. Automotive	2006 / 2007	The process is already patented but not yet industrialised	**Profiltechnik GbR (owner)** **Licences will be awarded**
Process cost analysis	Cost Analysis Software tool	Thermoplastics production industries	2008-2010	Patent Under Consideration	**LTSM**
Heat transfer analysis	Process model	Thermoplastics production	2008-2010	Under Consideration	**LTSM**

		industries			
TP RTM process	Manufacturing process	Aerospace automotive	2009-2010	Patent planned (2007)	**EADS IW**
Characterisation of manufacturing properties of CF/PEKK through comparison of autoclave versus press forming processing techniques.	Design data for CF/PEKK for autoclave and press forming methods. Quantitative data for angular and thickness dimensional variability.	High performance applications such as aerospace and F1	2005	Non-disclosure agreements in place with potential customers	**A-UK, IC**

2.2 DISSEMINATION OF THE KNOWLEDGE

The hereafter table summarises the (external & internal) communication about the DINAMIT results, which occurred during the program and what is foreseen in the next months.

Planned /actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible /involved
October 2004	Poster handout at exhibition	Trade fair for polymers	All	Several 10,000s	**LPW**
October 2004	Internet	General public	All	Internet	**LPW**
January 2005	Publication in JEC journal	Coppmposites Industry	Europe & worldwide	Large	**EADS IW Dassault Eurocopter**
April 2005	SAMPE Conference	Composite Industry & research	Europe	Large	**EADS.**
May 2005	SAMPE Conference	Composite Industry & research	Worldwide	Large	**Dassault EADS IVW**
April 2005	Poster at JEC exhibition in Paris	Composite Industry& research	Europe	Large	**EADS IW**
2004-2005-2006	Meetings with Airbus manufacturing plants& AIRUBS BUs,	Industry sector (Engineering, Manufacturing)	France	5 to 10 people	**Airbus France EADS IW**
2005-2006	Meetings with Airbus M&P depart and plants	Industry sector (Engineering, Manufacturing)	Spain	5 to 10 people	**Airbus ESPANA**
March 2006	Paper in the Parliament magazine	Public	Europe	Large	**EADS IW**
April 2006	Poster at JEC exhibition in Paris	Composite Industry& research	Europe	Large	**EADS IW**
JUNE 2006	Presentation at Aeronautics days (Vienna)	Aeronautics industry	Europe & worldwide	Large	**EADS IW**
AUG. 2006	ECCM12	Composite research	Europe & worldwide	Large	**IVW**
AUG 2006	Paper in Journal (submitted for publication)	Composite Industry & research	Europe & worldwide	Large	**LTSM**
Nov. 2006	SAMPE France	Composite Industry & research	France	Large	**Airbus France**
Nov 2006	IVW Kolloquium	Composite industry & research	Germany	Medium	**IVW**

FEBRUARY 2007	Paper in Journal (submitted for publication)	Composite Industry & research	Europe & worldwide	Large	**LTSM**
APRIL 2007	SAMPE Conference	Composite Industry & research	Europe	Large	**LTSM**
MAY 2007	Mesomechanics Conference (MESO '07)	Composite Industry & research	Europe	Large	**LTSM**
MAY-JUNE 2007	2 Papers in Journal (to be submitted for publication)	Composite Industry & research	Europe & worldwide	Large	**LTSM**
END2007	Publications (2) in reviewed journals	Research	worldwide	large	**LPW**
END 2007	Conference	Research	worldwide	large	**LPW**
MID 2008	SAMPE Conferences	Composite Industry & research	Europe & worldwide	Large	**EADS**
JUNE 2008	ECCM Conference	Composite Industry & research	Europe & worldwide	Large	**LTSM**

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