Robot based thermoplastic fiber placement process

The excellent specific stiffness and strength of carbon fiber reinforced composites makes them especially interesting for applications in rotating machines. Unfortunately, these materials have the disadvantage that their manufacturing process is labour-intensive, and thus slow and expensive. This drawback is overcome by the highly automated thermoplastic fiber placement process, in which impregnated thermoplastic tape is heated and then consolidated in situ under pressure. ABB has implemented the process in the laboratory with a 6-axis robotic system and is using it to develop new components for turbomachinery. The process is also of interest for applications in the aircraft and automotive industries.

Ongoing demand for improved performance and efficiency, coupled with lower costs, has led to manufacturers of high-speed turbomachinery and other dynamic systems stepping up their efforts to improve the properties of the materials used. For robot systems, with masses that have to be accelerated quickly, or rotors, which have to withstand high centrifugal forces, materials are required which combine high strength and stiffness with low weight. Fiber-reinforced composites fulfil these requirements better than standard materials, such as steel, aluminium or titanium alloys, on account of their extraordinary strength-to-weight and stiffness-to-weight ratios (*Table 1*).

While many types of composites exist [1], the most mature and promising materials for inertia-loaded structures are those based on carbon fiber reinforced polymers. The challenge involved in manufacturing structures made with these materials lies in the need to orientate continuous fibers in multiple directions.

In the traditional three-step approach 1, the laminate is first hand laid-up with unidirectional carbon fiber sheets 1a which have been pre-impregnated with a thermosetting resin. Next, an autoclave 1b is used to apply consolidation pressure and heat to harden, or cure, the resin. Finally, the material has to undergo quality control, usually based on ultrasonic inspection 1c.

Not only is this manufacturing process labour-intensive but the material scrap rate is high and repeatability is limited. Switching to carbon fiber tape impregnated with thermoplastic resin and employing an automated lay-up procedure circumvents these disadvantages, increases affordability, and leads to a wider range of applications and new levels of performance.

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Polymeric composite materials

In composites, the fibers are the principal load-carrying members and the surrounding polymer (or matrix) helps to position and transfer load between them while also providing protection from the environment. The most important characteristics required of a reinforcing fiber are low density and high stiffness and strength; several commercially available fibers satisfy these criteria (*Table 2*).

Polymers may be classed either as thermosets or thermoplastics [2, 3]. Thermoplastic polymers consist of individual chains of molecules which are not linked by chemical bonds 2a but by weaker secondary bonds such as van der Waals and hydrogen bonds. By applying heat and pressure, these bonds can be broken to deform the material to the desired shape. Upon cooling, the bonds maintain the new molecular positions. Thus, thermoplastic materials can be melt-processed. Besides their capability for being reprocessed as often as required, they are also amenable to welding.

A thermosetting polymer, as the name implies, cannot be reformed once it has 'set'. The molecules in a thermoset are chemically joined, or cross-linked 2b, and cannot be redefined through the application of heat and pressure. Historically, composite materials have been based on thermoset resins, and most of the available processes are based on this class of material.

Traditional manufacturing procedure for high-performance composites **1**

a *Laminate lay-up* b *Autoclave for curing* c *Quality control*

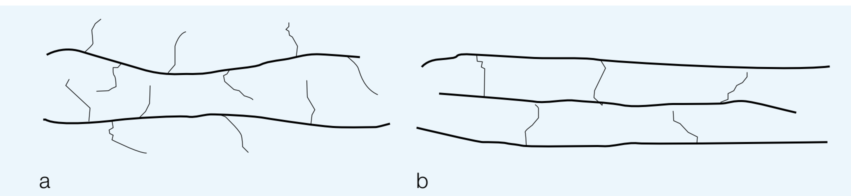
Traditional manufacturing of composite parts

The fiber reinforcement in a high-performance composite structure has to be continuous with well-defined orientations. Processes such as injection and compression moulding are not considered here as they are more suited to short-fiber composites.

Continuous reinforcement is achieved by hand laying woven or unidirectional fiber fabrics over a mould. A thermoset resin is then brushed on, or the fiber fabric is dipped in a resin bath beforehand or the resin is infused under a vacuum bag. An alternative and more elegant method is to use pre-pregs. These are sheets in which the fiber has been pre-impregnated with a controlled amount of thermoset resin and then partially cured to give it tack qualities rather like those of cellotape. After lay-up, the laminate is vacuumed and external pressure is applied to remove air and ensure wet-out of the fibers. Heat is then used to cure the resin. The heat and pressure are usually applied in an autoclave **3**.

Besides this manufacturing process being labour-intensive, the material scrap rate is high and repeatability is limited. These shortcomings were recognized in the early days of composites, and as a result the filament winding manufacturing process was developed to automate and mass produce composites. In this process, a tow of continuous fibers is wound onto a rotating mandrel. Before they reach the mandrel, the fibers are impregnated by passing them through a resin bath. Full

Thermoplastic (a) and thermoset (b) molecular chain **2**



wet-out is achieved by applying tension to the fibers during winding. The wound assembly is then placed in an oven for curing, after which the composite part is removed from the mandrel.

Early applications were tubular structures, but today more complex shapes, such as rowing oars and spheres, are possible. However, filament winding cannot be applied to all types of structures due to the following limitations:

- Use is restricted to bodies of revolution only. Flat and open sections are not practicable.
- Fibers can be laid only along geodesic paths, where tension can be applied.
- Plies parallel to the winding axis are not practicable.
- Complex shapes, ie concave or double curvature, are impossible.
- The quality of the laminate is limited.

The fiber placement process has evolved from filament winding and avoids the above problems. Instead of wet fibers being wound around a mandrel, a tape-laying head is used to lay down pre-impregnated thermoset tows onto a tool surface. With this process, complex contoured structures are possible, fibers can be laid exactly along the principle stress directions, and computer control reduces material scrap, enhances repeatability and improves quality.

Table 1:
Typical strength-to-weight and stiffness-to-weight ratios for different materials

Material	Strength/weight MPa/kgm^{-3}	Stiffness/weight MPa/kgm^{-3}
Steel	0.25	27
Al alloys	0.20	26
Titanium alloys	0.20	25
AS4/PEEK	1.40	84
IM6/epoxy	2.20	128

Table 2:
Typical properties of commercial reinforcing fibers

Fiber type	Fiber diameter µm	Specific gravity	Tensile modulus GPa	Tensile strength MPa	Failure strain %
E-glass (glass)	10	2.54	73	2,450	4.8
T-300 (carbon)	7	1.76	228	3,200	1.4
Kevlar-49 (aramid)	11.9	1.45	131	3,620	2.8

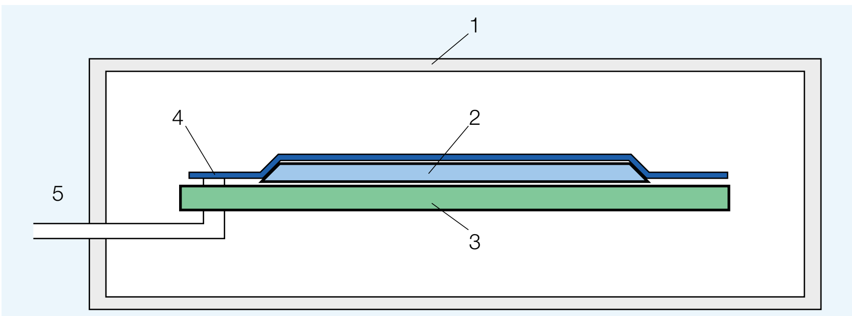
Robotics based thermoplastic fiber placement

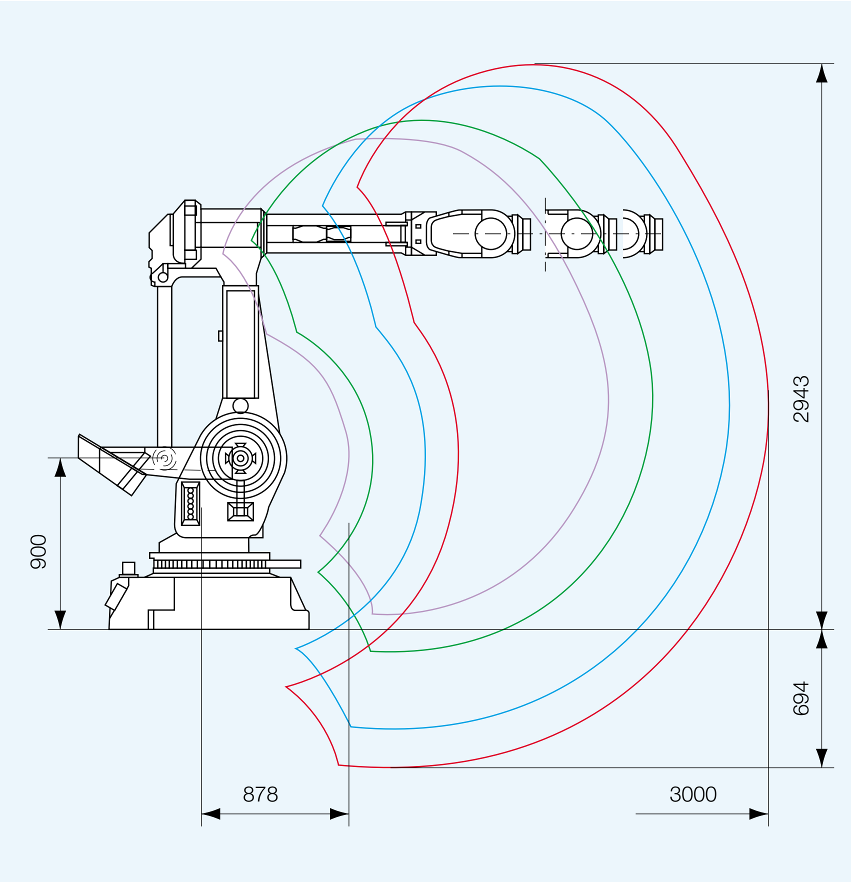
Despite its advantages, fiber placement has not found widespread use. The capital cost of the equipment remains high and only a handful of machines are in use worldwide. One reason for the high cost is the need for the thermoset pre-preg tows to be refrigerated upstream of the tape-laying head to prevent premature curing and then to be carefully handled during pay-out. The use of thermoplastic pre-preg tape overcomes these problems, since no special handling is necessary. Furthermore, by applying heat at the point of lay-down the thermoplastic tape can be consolidated in situ, so there is no need for autoclaving.

Another major factor is the cost of the multi-axial tape-laying head manipulator. Historically, these machines have been scaled-up versions of numerically controlled milling machines and are typically low-volume products [4, 5]. Recently, enormous progress has been made in the areas of cost, mechanical performance and control of 6-axis robots. For example,

Autoclave process **3**

1 *Autoclave*
2 *Composite*
3 *Mould*
4 *Bag (sealed)*
5 *Vacuum*

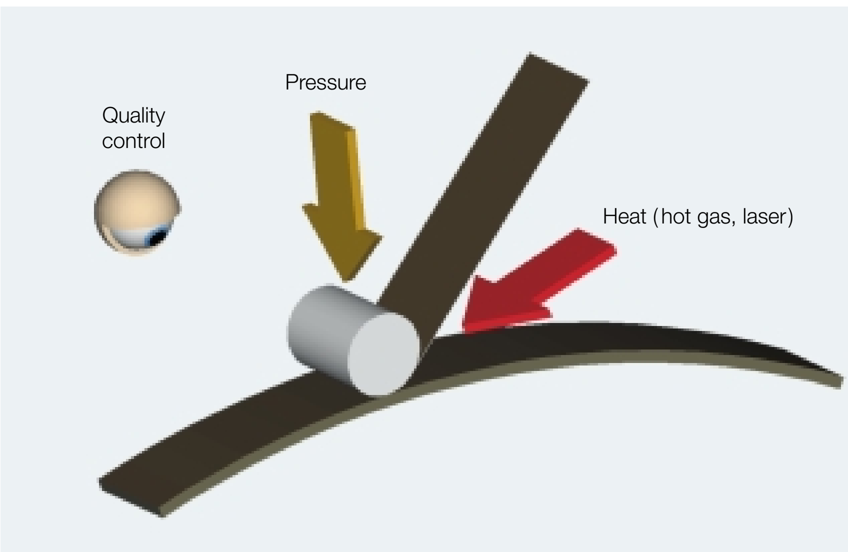




Type IRB6400 6-axis robot. This robot can carry a payload of 200 kg at speeds of up to 5 m/s with a path accuracy better than 0.1 mm. Different work envelopes are possible by using different manipulators. **4**

All dimensions in mm

Thermoplastic fiber placement process **5**



the ABB IRB6400 6-axis robot **4** can carry a payload of 200 kg at speeds of up to 5 m/s with a path accuracy better than 0.1 mm [6]. Equipped with modern control, these robots can function like numerically controlled machines and be used for complex tasks such as fiber placement.

The combination of thermoplastic composites and robotic technology has tremendous potential in the manufacture of affordable high-performance composites.

The Thermoplastic Fiber Placement (TFP) process is outlined in **5**. In TFP, a carbon fiber tow, impregnated with thermoplastic resin, is rolled onto a substrate and welded by applying localized heat at the 'nip' point (ie, the point of contact). A suitable head has been implemented on a 6-axis IRB6400 robot at ABB Corporate Research by the fiber placement equipment integrator Automated Dynamics Corporation [7]. This robotic workcell **6** also has an external spindle axis to allow bodies of revolution to be processed.

During the lay-up process the kinematic path of the robot has to be generated in such a way that the roller pressure always acts normal to the surface. Tape feed, tape cutting and pressure application are all process variables that have to be coordinated with the robot motion during strip lay-down, and have been integrated in the robot controller.

The nip point heat flux is applied by means of a hot nitrogen gas torch or by a Nd:YAG 1.5-kW continuous wave laser. Currently, heat flux management is not integrated in the robot controller. For torch-based heating, the gas temperature is regulated with the help of a thermocouple placed at the nip point; the thermocouple's signal is sent to a PID controller that governs the current in the torch heating element.

In the case of the laser, the power is regulated by a neural network controller based on pyrometric observations of the nip point temperature and the tape lay-down speed [8].

In a later step, the robot path planning will be combined with CAD and the composite layer build-up design. The integration of the part design, mechanical analysis and manufacturing process will not only drastically reduce manufacturing time, and therefore costs, but also reduce the interface problems and improve performance.

Modelling and control of the TFP process

The TFP process depends to a large extent on the heat transfer from the heat source (ie, the hot gas torch or laser) to the tape and on the cooling process afterwards. The process parameters have to be chosen correctly in order to obtain an optimum part quality. Heat transfer analysis and materials testing have been performed to find the ideal heating system [9] and process parameters, respectively. The process parameters (eg, speed and heat flux) have to be determined individually for each type of tape material.

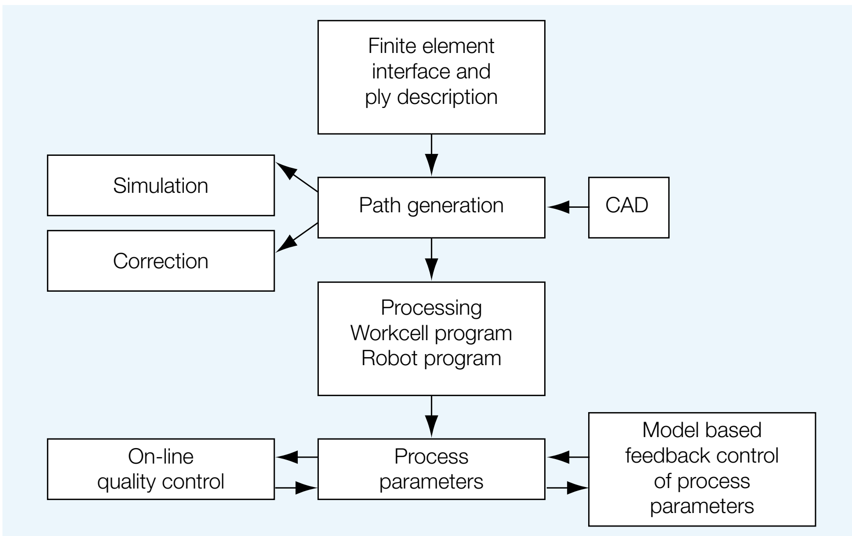
The TFP process is controlled on a PC with a LabView user interface. Dimensions and lay-up specifics, such as angles, plies, path crossovers, etc, are programmed and changed at the PC user interface. These values and the mandrel speed and head functions have to be combined with the control of the robot.

The quality of the part is largely dependent on the quality of the material bonding. Several direct and indirect methods are available for checking this. Laser ultrasonic testing is a possible method, but it has not been implemented to date. Temperature measurements taken shortly after the consolidation, combined with a good process model and sound knowledge of the materials, provides a reliable estimate of the laminate properties.

TFP robotic workcell at ABB Corporate Research in Baden-Dättwil **6**

Today, the process parameters are chosen according to the process models used and from material test data. If necessary, the values can be adapted manually during the winding process. In the future, the feedback from an on-line quality inspection device, as well as on-line measurement of process parameters, will be used as input for a model-based feedback controller **7**. Thus, automation

Flow diagram of the thermoplastic fiber placement process **7**



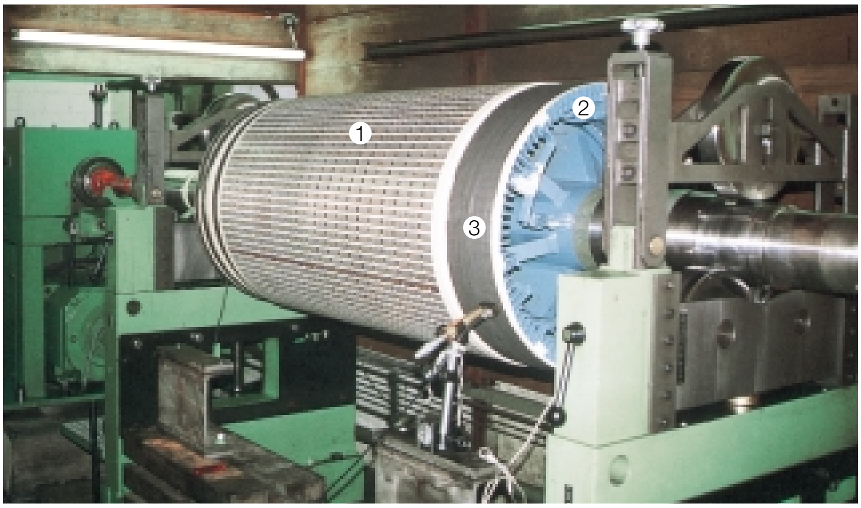


ABB motor with thermoplastic overhang bandage **8**

1 *Active part* 2 *Overhang* 3 *Bandage*

can be increased and the process will be even easier to use in an industrial manufacturing environment.

Industrial application for motor overhang bandages

For this industrial application the TFP process has been slightly modified and implemented in an ABB motor factory [10]. It is now used as part of the production process for electrical machines.

Copper bars are normally used for the rotor windings of electrical machines. Within the active part of the rotor, these conductors are held in place by wedges.

Beyond the active part, at each end of the rotor, the windings overhang to accommodate the turns. The influence of the centrifugal forces on the overhang is minimized by a retaining ring **8**.

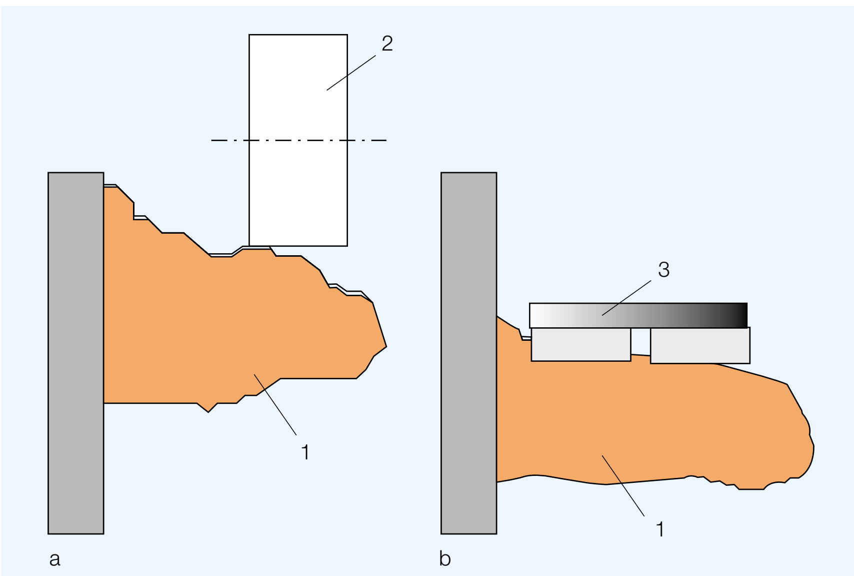
At the present time, ABB manufactures retaining rings for its electrical motors from either wound steel wire, glass/polyester composite material or steel rings. Steel rings are used for induction motors due to the higher demands these machines make on the material's strength. The rings are pre-machined and shrunk on the motor overhang, which makes the process expensive. The manufacturing process for the steel wire bandages is relatively slow; typically, one week is required to wind two rings on a motor rotor. The manufacturing process for the glass/polyester composite material is also laborious, with the entire rotor having to be preheated in an oven and then cured in an oven again after the ring has been wound. In addition, the thickness of both these ring designs impedes the heat flow from the rotor, reducing performance.

The use of thermoplastic-matrix composite materials in combination with automated TFP has major advantages for this application:

- Preheating of the rotor before winding and curing after winding are not necessary.
- Minimal or zero use of expendable materials.
- Carbon fiber and thermoplastic material properties improve performance: an increased strength-to-weight ratio results in thinner, lighter rings; the negative coefficient of thermal expansion promotes higher ring pretension; and higher thermal conductivity promotes rotor cooling.
- In situ consolidation produces bandages with higher and more consistent levels of retained tension, increasing quality and reducing the need for 'overkill' designs.
- With in situ consolidation, winding geometries which cannot be achieved

Overhang of an exciter rotor (a) before and (b) after winding with thermoplastic tape **9**

1 *Overhang* 2 *TFP roller* 3 *Retaining ring*



with the present thermoset process are potentially feasible.

- Rationalization of the process used to manufacture the overhang reinforcement through replacement of three systems (glass, steel wire and steel ring) by one (thermoplastic bandages).

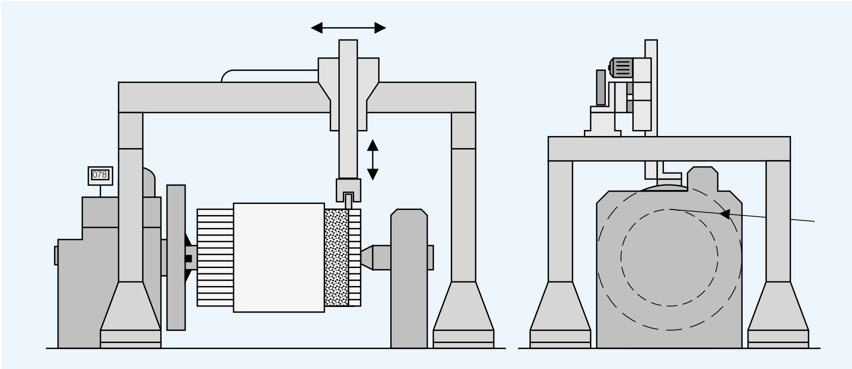
ABB manufactures motors and generators of many different types (squirrel cage and wound rotor induction machines, traction motors, synchronous machines, exciter rotors and DC motors). Consequently, the shape of the winding overhangs, the operating temperatures and the mechanical loads are also different.

The TFP process had to be adapted to the motor overhangs. Unlike mandrels, motor overhangs have a less well-defined surface and are flexible. In order to achieve the required prestressing of the bandage, a braking system was necessary. The brake force must be variable due to the overhang being flexible in the radial direction. A constant prestress over the axial length of the overhang would increase pressure in a flexible region and reduce the prestressing in other areas.

In addition, the winding must run continuously back and forth across the overhang to obtain an even pressure distribution. For narrow bandages, the robot path planning must be optimized to avoid uneven thickness build-up of the layers and prevent poor quality at the sides of the bandage. Loose carbon fibers at the sides must also be avoided to prevent short circuits in the electrical machine.

The robot path planning needs to be robust and must follow the surface deviations of the overhang. For instance, the overhang of exciter rotors used in synchronous machines is not only flexible but also has a conical shape with an uneven surface and varying diameter **9**.

The TFP machine in the motor factory consists of an ABB gantry robot with a modified TFP machine head **10**, **11**. The robot is programmed for normal operation on the robot user panel. A PC is used to control and analyze the TFP process parameters.

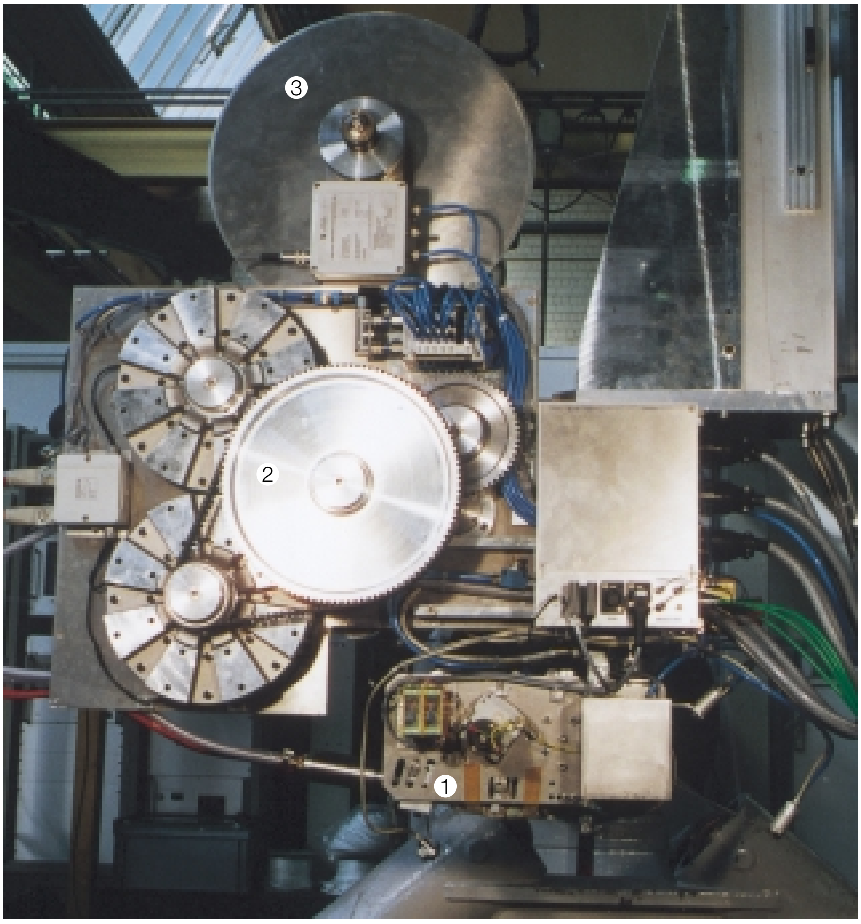


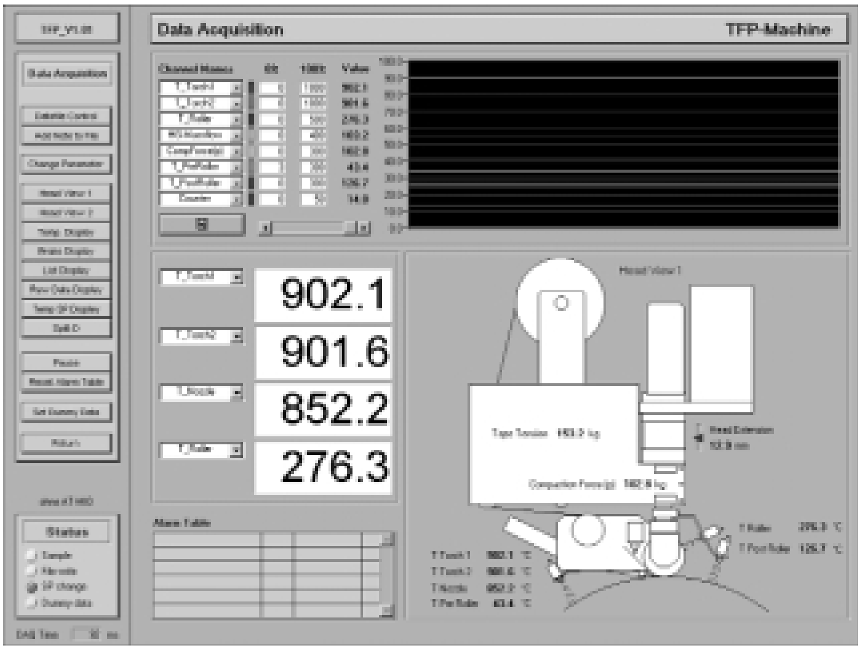
TFP machine and gantry robot arrangement in the ABB motor factory at Birr, Switzerland **10**

For applications in factory environments it is essential for the operator interface of the TFP process to be easy to use. All the

TFP machine head used in the motor factory at Birr **11**

1 *Compaction roller assembly*
2 *Brake system*
3 *Pre-preg tape spool*





LabView based user interface for monitoring process parameters, optimizing the process and testing **12**

input data needed to wind the motors is entered on the robot user panel. The high level of automation means that the machine can be operated by just one person – an important factor in ensuring the cost-effectiveness of the TFP machine.

A LabView user interface **12** is used to monitor the process parameters, optimize the process and carry out tests.

A cost-benefit analysis shows that the advantages of the TFP process translate into a major competitive edge over all other processes.

Summary and outlook

The high level of automation achieved with the robot based thermoplastic fiber placement process drastically reduces the manufacturing time for composites, and therefore their cost. In addition to being used in the laboratory, the process has also been successfully employed in the manufacture of motor overhang bandages in a factory environment. The robotics industry itself and also the aircraft industry are other sectors in which the TFP process offers important advantages over all other processes.

As a next step it is planned to further increase the process automation. A model-based feedback controller will make the process easier to use and should lead to even higher quality. Three-dimensional tape-laying will be implemented to close the gap between CAD and the robot path planning, which will reduce manufacturing time and costs even further. Also planned is the application of robot-based tape-laying to thermoset based composites. ABB is exploiting the TFP process internally to develop new composite applications for its range of turbomachinery products. At the same time, commercial versions of the TFP robot workcell are being planned to allow other industries to benefit from it.

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