

DEVELOPMENT OF A NOVEL TECHNOLOGY FOR RAPIDLY ROTATING SYSTEMS FOR MEDICAL TECHNOLOGY

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ABSTRACT

Rapidly rotating systems such as centrifuges are widely used in medicine and laboratories to efficiently separate different constituents of liquids. Rotors, which hold sample containers, are an essential part of centrifuges. Since they are subjected to extreme mechanical loads, rotors are one of a centrifuge's core safety components. Their deficits served as the point of departure for the development of a novel manufacturing technology, which is based on carbon fiber-reinforced polymers (CFRP). Its supporting structure is entirely in the loading plane, thus enabling the rotor to absorb higher centrifugal forces while requiring the same amount of material. The new design concept for the load-bearing structure includes a geodesically molded annular support member. It transmits forces better than present products and increases rigidity. In order to eliminate the known problems with obtaining the necessary manufacturing quality of hollow fiber composite bodies, the authors developed the process of centrifugal infusion. Their proposed solution is based on generating higher gravitation forces, thus effectively eliminating detrimental gas pockets and simultaneously optimizing surface quality and impregnation.

KEYWORDS

laboratory centrifuges, carbon fiber rotors, composites, lightweight, hybrid systems, additive manufacturing, medical technology.

Introduction

Both the chemical and pharmaceutical industry and medicine use laboratory centrifuges to separate various substances. Centrifuges use inertia to separate substances. Higher density particles are pushed outward, lower density particles land in the center.

Rotors, which hold sample containers, are an essential part of centrifuges. Since they are subjected to extreme dynamic stresses during centrifugation, they must be engineered to satisfy the highest safety standards.

During centrifuging, the stronger gravitational field produced by the centrifugal forces generated by rapid rotation cause a solution's solid constituents to

precipitate. In this stronger gravitational field, constituents with greater mass displace lighter particles, which are thrust closer to the axis of rotation. The gravitational force increases exponentially to the distance from the axis of rotation (radius).

Centrifugal forces, equivalent to 25,000 times the force of gravity, act on rotors and samples rotating at speeds of up to 20,000 revolutions per minute. Until now, the load-bearing structures of centrifuge rotors have been made of special aluminum alloys and thus relatively easy to manufacture.

The drawback of this technology is the rotors' rather high weight of around twenty-five kilograms, which elevates energy consumption and puts greater mechanical stress on the entire centrifuge system.

Furthermore, aluminum rotors that can fracture are critical. In the worst case, the kinetic energy dissipated in the safety enclosure can be comparable to the impact of a car going eighty-five kilometers per hour with a concrete wall!

Given this stress profile, fiber-reinforced composites appear to be the ideal material for centrifuge rotors. The anisotropic properties of carbon fiber-reinforced materials must always be taken into account, however, especially during the development of a systematic methodology for the production of lightweight rotors made of carbon fiber-reinforced polymers. After all, the fibers' very high tensile strength and stiffness can only be exploited fully when they are optimally aligned in the direction of loading [1].

Motivation

In response to the problems outlined above, the authors developed a novel technology that manufactures lightweight rotors using pre-molded, woven carbon fibers.

Carbon fiber's high tensile strength in the direction of loading can be exploited ideally, especially in long profiles and flat or cylindrical forms. Conical and freeform surfaces like those in centrifuge rotors are more complicated, though, since fibers have no support on such surfaces and slip easily. That is why only winding is presently applied to manufacture rotors. The inability to align the fibers in the direction of loading is a drawback, however [2]. Furthermore, very expensive multi-axis winding machines are needed to manufacture wound rotors. Moreover, wound surfaces are never really smooth and this affects a rotor's running smoothness adversely.

The new method therefore employs carbon spiral tapes with the on conical surfaces, the fibers of which are aligned in the direction of loading. Their geometry corresponds exactly to the rotor's wound conical surface.

The complicated design principle envisioned by authors necessitates appropriate molds that reproduce complex geometries such as undercuts. For this reason, additive (laminated) methods of generating geometry are used to make molds. Given their practically unlimited freedom of design, these technologies can be used, for instance, to produce cup volumes close to the edge with accurate contours while the mold is being made. Furthermore, the geometrically complex inserts produced by selective laser sintering (SLS) reduce the weight of rotor bodies substantially.

Successfully implemented, the novel concept should make carbon rotors around 10–15% more stable and simultaneously lighter than lightweight aluminum rotors. Furthermore, the permissible speed is expected to be at least 10% higher than that of presently available lightweight rotors of the same class.

Numerical calculation and simulation

First, extensive physical models and new calculation algorithms were developed for the FEM analysis, which were intended to ensure that lightweight rotors can be manufactured reproducibly in order to implement this in practice in the future.

Simulation systems [3] are also used in the optimization process to evaluate the envisioned mold geometry. They can be used to simulate the layering process iteratively and localize problem points or even collisions [4].

One fundamental task was to quantify the principal stresses that occur during centrifugation and the resultant critical zones in the rotor geometry. Important conclusions about the rotational energy were drawn from the subsequent energy analyses of different rotor geometries (a conventional aluminum design, a monolithic CFRP rotor and a CFRP rotor with laser sintered cores). The composite CFRP design with a laser sintered cored delivered the best results (model Core 2).

First, CAD models of the two rotor sizes (14×50 ml and 6×500 ml) analyzed were generated. They served as the basis for subsequent calculation of the shell design and potential failure criteria (maximum stress, maximum strain and so forth) with the finite element method (FEM), Fig. 1.

Calculations were done with the ANSYS analysis package, which allows extensive and very precise calculations of fiber composite materials with its tool "Composite PrepPost". This tool exactly ascertains and calculates the principal stresses occurring during centrifugation and the resultant critical zones in the rotor geometry [5] (Fig. 2).

Taking the requisite properties of the rotor as the starting point, an energy analysis of three different rotor geometries was performed first in order to draw conclusions about the rotational energy of each (Table 1). The target specified for the complete system was 94,000 Nm. Only the "Core 2" model met this target (see Table 1). When it had not been optimized, the rotor geometry designed as a monolithic CFRP block (CFRP) even worsened the initial values.

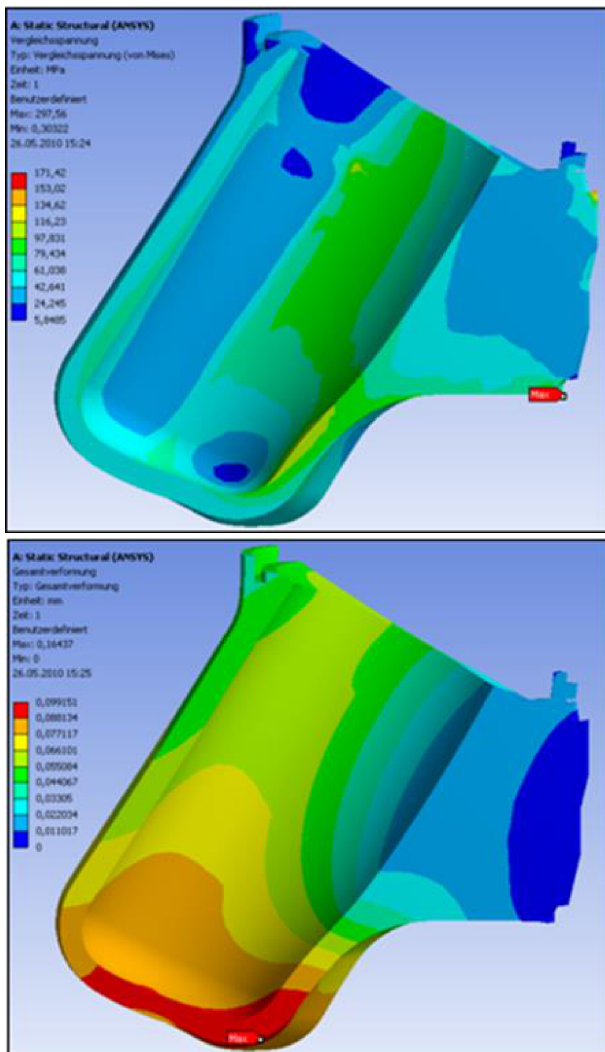


Fig. 1. Calculation of a CFRP rotor’s main parameters – e.g. comparative stresses according to v. Mises (N/mm²).

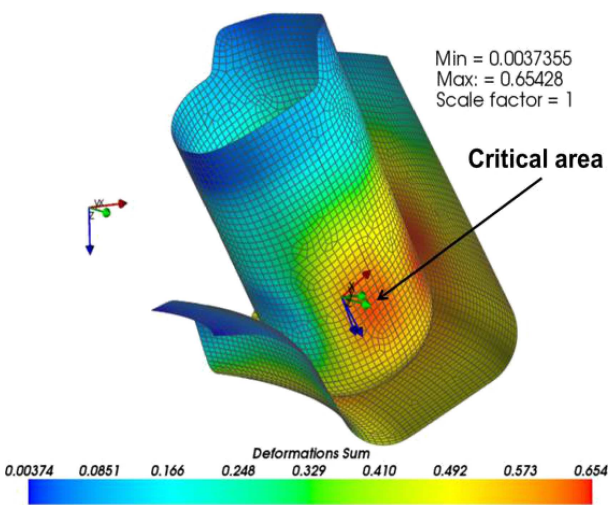


Fig. 2. Critical rotor geometry zones and deformation (unit of measurement millimeter).

Table 1
Energy analysis of a 6 × 500 ml CFRP rotor compared with an aluminum rotor.

Rotational energy [Nm]			
Type	Rotor	Target	Difference
Aluminum	154.246	94.000	60.246
Monolithic CFRP	158.913	94.000	64.913
Core 1 – foam	135.208	94.000	41.208
Core 2 – foam SLS	86.426	94.000	-7.574

Following the energy analyses, ANSYS was also used to calculate the joined structure and the optimal thickness of the layering of the mold with the carbon fiber mats and spiral tapes for both models. The structure was optimized, thus raising the complete system’s safety factor from 2.3 (conventional aluminum rotor) to 3.0 (CFRP rotor). Furthermore, the calculations performed revealed the unsuitability of the geometry of model 1 (the monolithic CFRP) since it is more prone to deform in undesired ways. For this reason, it was eliminated from the subsequent stages of development.

The energy analyses and FEM analyses confirmed that model 2 (Core 1 foam) and model 3 (Core 2 foam SLS) have enough potential for optimization for rotational energy and absorbed stresses. These analyses indicate that the use of a reinforcing annular support member is decisive for the rotor’s potential for optimization. When it has a content of approximately 55% fibers by volume, this support member can reduce the weight of carbon fiber rotors produced with the novel technology by up to 44% over conventional aluminum rotors.

This is primarily attributable to the densities of the CFRP non-crimp fabric (1.5 g/cm³) and the foam of the filling elements (0.13 g/cm³), which are substantially lower than aluminum (2.7 g/cm³).

This weight advantage will shorten acceleration and deceleration times while retaining centrifuge performance and thus shorten cycle times. What is more, higher speeds can be run and, thus, higher relative centrifuge acceleration can be reached. A second effect of this weight reduction is the simpler handling of such rotors. Their resistance to corrosion and better fatigue strength are additional advantages.

Mold design

One of the major challenges during development was the design of the mold, which had to incorporate both the rotor’s geometric complexity (mold release characteristics) and the precise layering of fiber mesh computed in advance. Defined layering of the mold is important for the complete impregnation of the

fibers in order to obtain a uniformly high content of fibers by volume in the casting compound. Both are crucial prerequisites for the production of extremely stable centrifuge rotors.

The new concept was prototyped for rotors sized 14×50 and 6×500 , the first number denoting the number of sample containers and the second the size of the containers in milliliters. A complete rotor consists of nine components: an aerosol ring, a hub, the rotor itself and six filling elements.

The first step entails making a base body that holds sample containers and a hub with a conical exterior shape. Then, the spiral tape is wrapped around the base body. Since the spiral tape and base body have corresponding geometries, the spiral tape remains in its position without any other measures and the two ends of the tape merely have to be secured with a bit of spray adhesive. Afterward, the base body layered with spiral tape is placed in a second mold and impregnated with resin by centrifugal infusion (see the section on quality assurance below). This design reduces the moment of inertia by more than half.

Support from Additive Manufacturing Technologies

Since the mold's design is so challenging, additive processes such as laser sintering [6, 7] were used to make its geometrically complex areas. Thus, even undercut or, when necessary, close-contour geometries can be produced when the mold is being made.

SLS is employed to make the master models and vacuum casting to duplicate the molds. In particular, the filling elements of the cup recess with its many complex freeform surfaces can be produced by additive manufacturing significantly faster and less expensively than by conventional manufacturing methods. Taking the design specification as the starting point, so-called displacers (as inserts), among other items, were made for the rotor mold and additively manufactured by laser sintering (Fig. 3). These measures supporting design expedite mold making considerably and minimize costly and time-consuming reworking or even re-making. What is more, they allow the inspection of critical transitions between adjacent mold elements and the potentially necessary optimization of the layering of fibers.

The use of laser-sintered inserts not only reduced weight but also significantly lessened the rotational energy. Arranged in position, the inserts' job is to assure that Core 2 has the rotational energy desired.

The prototyping technologies of selective laser sintering and vacuum casting were combined to de-

liver the large quantities required. In parallel, the complete design was optimized to accommodate fiber composite materials.



Fig. 3. Selective laser sintered components of a cup recess in a CFRP rotor segment.

Prototyping and testing

Once the theoretical calculations had been completed, first rotor prototypes were produced to review the variation analysis. Laminating molds were made in order to assure reproducibility to manufacture larger quantities.

The greatest challenge during development was reconciling the molds' designs with the layering technology developed. Defined layering of the mold is crucial for the complete impregnation of the fibers in order to obtain a uniformly high content of fibers by volume.

Although the technology for layering the mold with CFRP mesh proved to be highly complex as expected, it is fundamental for the mass production of the rotors and the assurance of their property profile. Diverse approaches were therefore developed and their suitability verified. Ultimately, CFRP non-crimp fabrics were employed. They reduce the lateral forces under stress and can thus be employed significantly easier and faster during assembly. What is more, they slightly increase the stiffness and the layers of CFRP can be expected to delaminate comparatively less [8]. In addition, Prepregs were employed, which encase 50–55% of the fibers with resin in order to assure the optimal content of fibers by volume reproducibly.

The complete lightweight rotor consists of nine different components, namely the aerosol ring, the hub, the rotor and six filling elements. The lightweight plastic filling elements are hidden in the rotor housing between the cup holders and serve to reduce the weight of the lightweight rotor. (See the first proposed solution for the mold in Fig. 4.

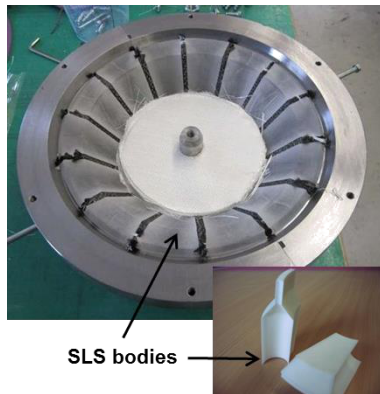


Fig. 4. Mold with carbon fiber mats and SLS bodies prepared for casting (open).

The hub is force fit with the rotor when it is being manufactured or layered. At present, the plan is to use two different hubs. The plastic aerosol ring is made separately and bonded with the rotor once it has been produced. Furthermore, the most complicated layering was subjected to applied tests. Mold assemblies were also supplemented with laser sintered parts.

This approach made it possible to alter the design quickly within a few hours, thus enabling the development partners to find and verify solutions for the most complicated layering steps in very short time (see Fig. 5 for a first rotor prototype).



Fig. 5. Operational prototype of a carbon rotor for a laboratory centrifuge.

Quality assurance of the novel centrifugal infusion technology

All of the methods presently applied to manufacture cylindrical or hollow fiber composite bodies such as centrifuge rotors make only limited manufacturing quality possible. Complex finishing methods have to be employed afterward to obtain high-quality surfaces in order to meet the standards of expen-

sive and extremely stable products. This increases manufacturing costs significantly, however, and thus makes the marketing of the products difficult. The impregnation of the fibers also requires much labor, but without obtaining the desired optimum for the stability of the fiber composites. Furthermore, the established manufacturing methods cannot evacuate detrimental gas pockets fully from fiber composite materials [9, 10].

In order to eliminate the aforementioned drawbacks, the authors developed the novel method of centrifugal infusion with which all of the aforementioned centrifuge rotors were made.

Technical goals included the development of both the system and the process.

The proposed solution is based on generating higher gravitational forces, thus effectively eliminating detrimental gas pockets and simultaneously optimizing surfaces and impregnation.

In the first step, basic tests were employed to define a basic model that can iteratively optimize the complete system's speeds, pressure transmission and resin filling process in several series of tests.

The software tool "EMELI", developed by the authors on the basis of Modelica and Dymola, provided important support. It was used to specify, model and simulate the infusion process digitally (virtual engineering) parallel to system development.

The heart of the new system is a rotary table with four jawed chucks that holds the rotor mold, which sets the mold rotating and thus generates a higher gravitational force. Other principle components are elements that of a resin injection system and gas venting system as well as actuators and bearings. A safety barrier (not shown) completes the centrifugal infusion system.

An automated system was designed to meet, maintain and monitor the parameters essential for quality assurance. The manufacturing parameters are monitored online over integrated sensors. (See the laboratory prototype in Fig. 6.).

Use of centrifugal infusion technology generates the following benefits:

- Reduction of the rejection rate of 15–25% at present to <5%;
- Attainment of requisite surface qualities without reworking or applying gelcoat beforehand, thus reducing the manufacturing time by approximately 20%;
- Improvement of the mechanical property profile of the fiber composites;
- Improvement of stability (no flaws or cavities);
- Acceleration of the resin injection process from >1.5 h to a few minutes.

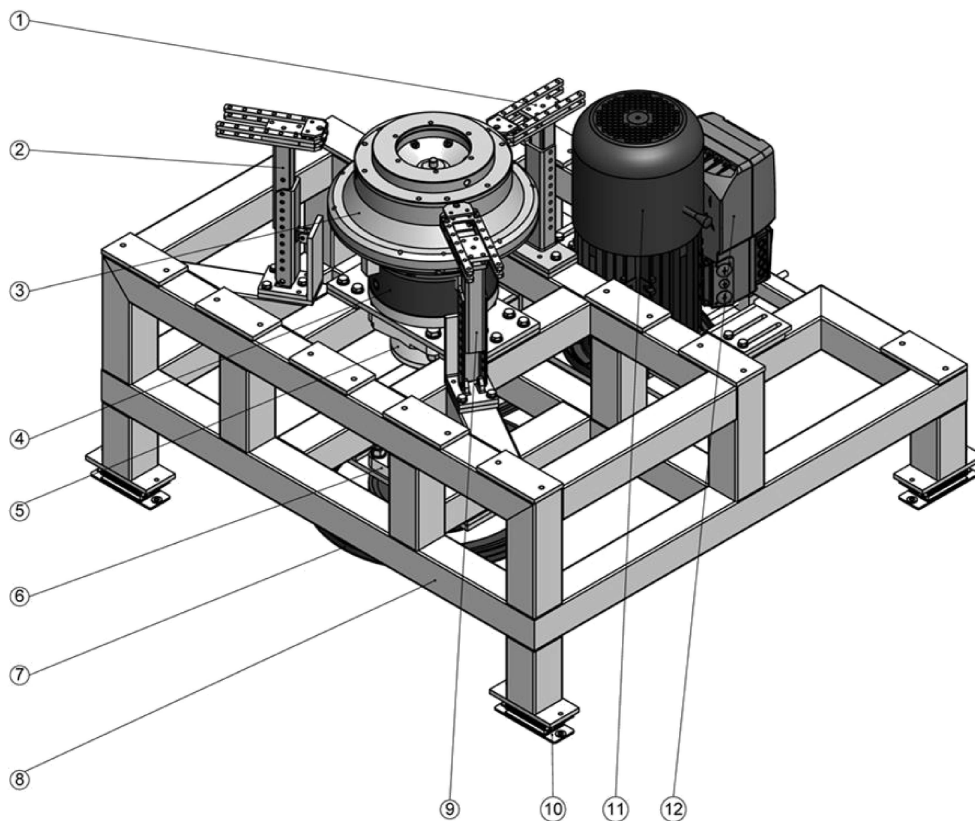


Fig. 6. Schematic of the automatic centrifugal infusion system. 1 – Front crash protection, 2 – Front left crash protection, 3 – Rotor mold, 4 – Four jawed chucks, 5 – Fixed spherical roller bearing, 6 – Floating spherical roller bearing, 7 – Toothed belt pulley, 8 – Frame, 9 – Front right crash protection, 10 – Damping element, 11 – Actuator, 12 – Variable-frequency drive

Ultimately, the new technology reduces manufacturing costs by up to 50% and makes it possible to manufacture high-quality products reproducibly.

Conclusion

In this project, an entirely new concept for the manufacture of fiber composite centrifuge rotors was developed, tested and finally optimized. To do so, energy analyses and FEM analyses were performed at the outset. First, based on 3D CAD models, the shell design and the potential failure criteria such as maximum stress, strain and so forth were ascertained using efficient computational tools. Afterward, the rotor geometry's weight and stability and the options for its manufacture were optimized.

Ultimately, both the laminating mold and the mold were designed and modified for the production methodology. Different additive manufacturing methods such as selective laser sintering and 3D printing were very useful control media that could be employed systematically.

Filling elements, made of polymer powders in the additive manufacturing process of SLS, particularly cut weight. In addition to consuming less energy and running more smoothly, the entire system is most notably subjected to significantly less mechanical stress than aluminum models.

The system is designed to be flexible and can produce up to 1,000 rotors of different sizes per year.

Having concluded the project, the authors now have a system, that produces fiber composites by means of centrifugal infusion and which is ready for mass production as well as the technology for essential processes, including resin injection and gas venting.

Use of centrifugal infusion technology generates the following benefits:

- High quality surfaces through homogeneous outer contours;
- Improvement of mechanical properties of the fiber composite structure;
- Reduction of the rejection rate of CFRP centrifuge rotors from fifteen to twenty-five percent at present to less than five percent;

- Shortening of the injection process from over one and a half hours to around ten minutes;
- Reduction of manufacturing costs by up to fifty percent, e.g. for CFRP centrifuge rotors sized 6×500 ml.

The extensive work to design and develop the layering technology delivered findings that will enable users to completely (re-)engineer their manufacturing processes without having to modify a mold's design. Rotors manufactured with the new methods combine the smooth surface of aluminum rotors with the advantages of wound rotors, e.g. lower weight and better fracture characteristics. The new lightweight rotors weigh up to fifty percent less than aluminum rotors and can withstand loads that are up to twenty percent higher.

The new method can produce smaller quantities more cost effectively than methods of wound rotor production. Furthermore, rotors produced by the new method are more stable and have a smoother surface and thus run more smoothly.

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