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Enhancing the Performance of Laboratory Centrifuges with Carbon Fiber Rotors

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Abstract. Centrifuges have multiple uses in medicine and in laboratories, most notably to separate sub stances such as blood plasma and serums. A centrifuge's rotors hold sample containers. Centrifugal forces equaling 25,000 times the force of gravity act on rotors and samples at speeds of 20,000 rpm. Unlike present conventional solutions (rotors made of special aluminum alloys), the load-bearing structures of the lightweight rotors presented here are made of carbon fiber-reinforced polymers (CFRP). The complex rotor and mold geometries are selective laser sintered. Given the fibers' extremely high load-bearing capacity, lightweight rotors manufactured with this novel technology set new standards for weight, stability and service life compared to current concepts. Moreover, this can reduce the warm-up time typical for aluminum rotors by at least fifty percent.

Keywords: Composite and Polymer Manufacturing, Additive Manufacturing, Forming Processes, Carbon Fiber Material, Centrifuges, Design.

1. Introduction

Centrifugation is the process most frequently applied to separate materials in liquids. Most notably, they are used to separate materials, e.g. blood plasma and serums, and produce genetically engineered substances.

A centrifuge consists of a housing, a drive unit with controller, a rotor, a safety enclosure and, frequently, a cooling system. The rotor holds sample containers. There are rotors for different sizes of samples (from the microliter range to one liter) and numbers of sample containers (depending on the task). They are subjected to extreme mechanical loads. Technically this makes them core centrifuge components.

During centrifuging, a solution's solid constituents precipitate under the effect of a stronger gravitational field produced by the centrifugal forces generated by rapid rotation. 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 exponential to the distance from the axis of rotation (radius). Superior centrifuges operate at high speeds of frequently more than 20,000 rpm. This produces gravitational fields, which exceed normal gravitation several thousands of times over. Conventional rotors are made of special aluminum alloys. They are relatively easy and cheap to manufacture but have drawbacks in terms of their stability and attainable rotational speeds. In addition, undesirable imbalances frequently appear.

Therefore, lightweight rotors are alternatively made of fiber composite materials. A variety of methods exist but, at present, only rotors with resin transfer molded bodies and wound highly stressed annular shells are commercially available.

Admittedly, lightweight rotors made entirely or partially of carbon fiber-reinforced polymers or mixed are more expensive than conventional aluminum rotors since they are predominantly manufactured by hand. However, in addition to having a substantially lower density, they weigh far less and are approximately six times more stable than aluminum rotors.

Lower weight cuts centrifuges' energy consumption and ramp-up times and also reduces an overall centrifuge system's mechanical loads. In addition, lighter CFRP rotors simplify handling since aluminum rotors often weigh up to 50 lbs.

2. Motivation and Aims

The authors jointly developed a method of manufacturing lightweight rotors from pre-molded woven carbon fibers. Carbon fibers have high tensile strength, provided the fibers are aligned with the direction of load. They are thusly processed relatively easily when profiles are long and shapes are flat or cylindrical.

However, tapering and freeform surfaces like those of centrifuge rotors are more complicated since the fibers are unable to adhere to these surfaces and slip easily. Hence, rotors are only wound at present.

The drawback of this is that the fibers cannot be aligned with the direction of load. Further, the manufacture of wound rotors requires extremely expensive multi-axis winders and wound surfaces are never really smooth. This affects a rotor's running smoothness adversely.

The new methods of positioning fibers aligned with the direction of load on conical surfaces employs carbon spiral tapes that exact match the winding of a rotor's tapered surface geometrically. In a first step, a base body that holds sample containers and a hub with a conical exterior shape are manufactured. Then, the spiral tape is placed around the base body.

Since the geometry of the spiral tape and base body corresponds, the spiral tape stays in place and only the two ends of the tape have to be secured with some spray adhesive. The base body layered with spiral tape is placed in a second mold and impregnated with resin by RTM. This design reduces the moment of inertia by more than half.

The complicated design principal considered by these authors requires suitable forming tools that reproduce the complex geometries (e.g. undercuts). Therefore, generative (laminate) methods of geometry generation are used to make molds. Given their practically unlimited freedom of design, these technologies can, for instance, already produce close-contour cooling channels during mold making. Furthermore, selective laser sintered, geometrically complex inserts reduce the weight of rotor bodies.

When this novel concept is successfully implemented, a lighter weight CFRP rotor will be at least 10 % more stable than a lightweight wound rotor. At the same time, it can be expected to have a permissible speed that is at least 10 % higher than that of lightweight rotors in the same class. First, comprehensive physical models and new calculation algorithms for the FEM analysis were developed, which ensure that lightweight rotors can be manufactured reproducibly for future implementation in practice.

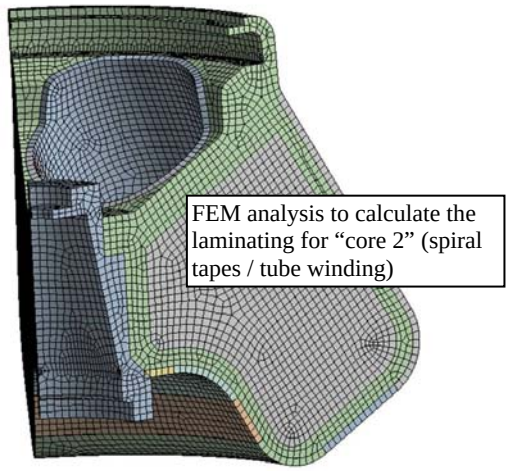

Fig.1. Rotor design calculation and simulation

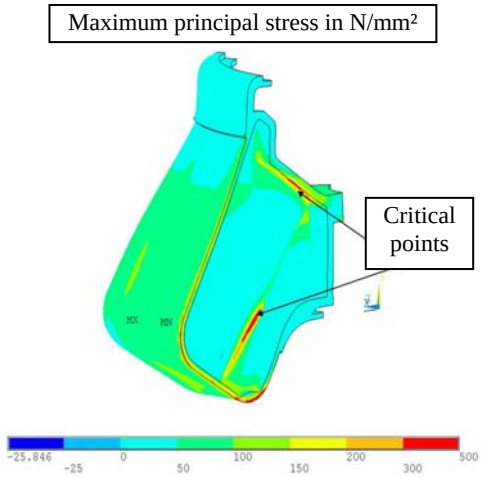

Fig 2. Critical rotor geometry zones.

3. Conceptual Design of the Manufacturing Technology

First, the CAD models of the two sizes of CFRP rotor analyzed (14 x 50 ml and 6 x 500 ml) were generated. They served as the basis for subsequently calculating the shell design and potential failure criteria (maximum stress, maximum strain, etc.) based on the finite element method (FEM), Figure 1.

The ANSYS analysis package was used for the calculations since it contains tools that are especially effective for the calculating the structures of fiber composite materials.

This tool was also used to identify and calculate the principal stresses produced during centrifugation and the resultant critical zones in the rotor geometry (Figure 2).

Taking the properties required of the rotor as the point of departure, the energy of three different rotor geometries was analyzed in order to draw conclusions about the rotational energy of each. The goal targeted for the overall system was 94,000 Nm. Only the variant "Core 2" met this goal (see Table 1).

Since the geometry had not been optimized, designing the rotor geometry as a monolithic CFRP block even worsened the initial values.

The simulation determined that CFRP rotors weigh up to 44 % less because they have a lower density (approximately 1.5 g/cm³ at a content of approximately 60 % fiber by volume) than aluminum (ca. 2.7 g/cm³) rotors.

This weight advantage shortens acceleration and deceleration times while retaining a centrifuge's performance. Consequently, cycle times are shorter.

Table 1. Energy analysis of a 6 x 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-SLS	86,426	94,000	-7,574

In addition, higher speeds can be run, thus increasing the relative centrifugal acceleration. Moreover, this weight reduction makes such rotors easier to handle. Their resistance to corrosion and enhanced fatigue strength are additional advantages.

4. Forming Tool Design

Taking the calculation results as the starting point, so-called displacers (as inserts) for the rotor casting mold were designed and laser sintered (Figure 3a).

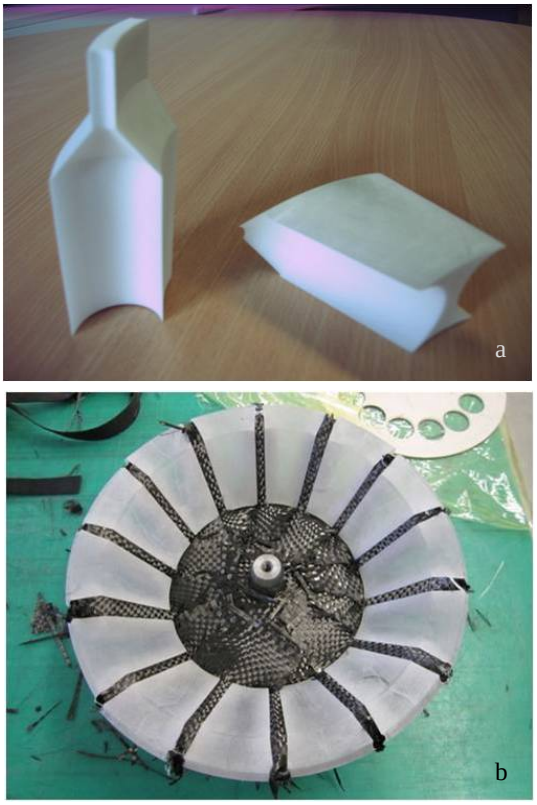

Fig 3. Selective laser sintered master models displacersas the basis for silicone molds (a). Rotor variant Core 2 with 14 inserted SLS cores (b).

In addition to cutting weight, such laser sintered inserts significantly reduced the rotational energy. Arranged in position, the inserts are intended to assure Core 2 has the rotational energy desired.

The prototyping technologies of selective laser sintering and vacuum casting were combined in order to deliver the large quantities required. The overall design was simultaneously optimized for fiber composites. The prototyping technologies of selective laser sintering and vacuum casting were combined in order to deliver the large quantities required. The overall design was simultaneously optimized for fiber composites.

5. Laboratory Prototype and Mold Making

The results of these tests entered into the development of the manufacturing technology to properly design the future forming tool for casting.

Taking the theoretical calculations as the starting point, initial rotor prototypes were subsequently produced to verify the variance analysis. This entailed producing laminating molds to assure the reproducibility of the manufacturing in certain quantities. One of the first rotor prototypes is pictured in Figure 3b.

The complete lightweight rotor consists of nine different components, including the aerosol ring, hub, rotor and six filling elements. The filling elements are hidden in the rotor housing between the sample container holders and are made of a lightweight plastic, thus reducing the lightweight rotor's weight.

Fig 4. Elements of the casting mold for the first rotor prototypes.

The hub is force fit with the lightweight rotors while it is being manufactured/layered. The use of two different hubs is planned at present. The aerosol ring is separately made of plastic and subsequently bonded to the rotor once it has been manufactured. The greatest challenge during development was reconciling the design of forming tools with the layering technology to be developed (Figure 4).

The forming tool must have the rotor's geometric complexity and its design must facilitate the defined fiber layering, which is crucial to facilitating full impregnation and a uniformly high content of fibers by volume.

These are essential for the manufacture of extremely stable rotors. Therefore, the development partners employed simulation methods to optimize the layering technology and to design the forming tools.

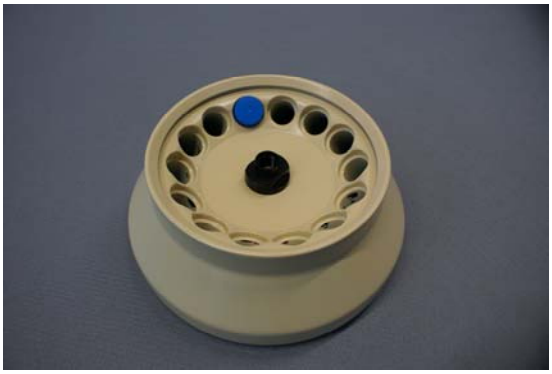

Fig 5. First solution for the carbon fiber rotor.

The tests executed made it possible to implement design modifications in a matter of hours, thus enabling the development partners to rapidly find and test solutions to the most complicated layering steps. The first proposed solution for the carbon fiber rotor is depicted in Figure 5.

6. Conclusion

The extensive work to design and develop the layering technology delivered findings that enabled carbonic GmbH to completely engineer its manufacturing processes without having to modify the 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 up to twenty percent higher loads.

Compared with wound rotors, the new methods can produce smaller quantities more cost effectively. Further, rotors manufactured with the new methods are more stable and have a smoother surface, which enables rotors to operate smoothly.

7. Acknowledgements

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8. References

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