Design and Implementation of SMC Components for an Automotive Electric Water Pump

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ABSTRACT: The automotive electrification open doors for new powder materials, manufacturing methods and assembly routines that are found to be very cost-effective. Soft-magnetic composites (SMC) show great potential to fulfill these demands by both significant size- and weight reduction of the active parts in the electromagnetic circuit. The result will not appear by using traditional thinking but will require openness towards both new routes and new investments to deliver the desired values. The new SMC components must be designed to enhance both magnetic performance, as well as the production of components and assembly into applications and systems to improve productivity and save costs. This case study provides an analysis and overview of the route to produce an SMC based electric motor for an automotive cooling water pump to fit in a hybrid or full electric car. The results of the study show a concurrent engineering approach for creating an optimized magnetic design combined with component and tooling design adapted for high-volume production. The SMC component is further matched to a dedicated press showing the way to a high efficient manufacturing line that can meet the demands of higher quality and cost-effectiveness. The performance of the motor is verified by prototypes made from net-shaped pressed SMC components. The outcome of the study is aimed to advise a state-of art SMC component process including design, manufacturing and assembly aspects for a potential automotive electrification application
Keywords:
SMC, soft-magnetic, powder, component, automotive, water pump, axial-flux, electric, motor, design, compaction, heat-treatment, manufacturing, tool, furnace.

1. Introduction

The present study is about a small electric water pump for electrified vehicles like BEV, HEV/PHEV or even likely for future adapted ICE driven vehicles using extended electric systems for auxiliary functions. The idea of an electrically driven water pump is not new at all, except for the automotive market. One of the main question raised in this paper is if it is possible at all to compete with traditional electric motor technology for such a quite simple application.

The ongoing dramatic trend of electrification in automotive applications is a double-edged sword for established suppliers to this huge industry. Radical changes like new system solutions and a never ending press of costs will put high pressure on business development and investments to keep and expand the market positions in the future automotive landscape. The powder metallurgy route has created a lot of value for automotive businesses over a number of decades with its proven efficiency, mostly in cost-per-performance for high volume production of mechanical sinter metal components. Many of these components are directly connected to the internal combustion engine that most probably will be radically downsized and also replaced by electric drive systems in the very near future. The traditional belt-drive for auxiliary functions will also be changed into more flexible, controllable and energy efficient electric applications such as A/C compressors, oil and water pumps. The benefits of this development include improved functionality, alternative positioning in the vehicle that lead to direct cost-savings. The latter is intimately connected to the reduction of mechanical components and their complexity, as well as the often more simple production processes involved for the electrical solution.

The route to a more cost-effective water pump set-up proposed here rests on factors such as weight reduction and the simplification of components, as well as assembly processes. A successful solution will then be found to be more compact in all over dimensions, but the most important factor for cost reduction will still be connected to the weight. Noise and vibration are also among the most critical factors for a modern electric water-pump since it will often continue at standstill. With the drive motor off, even low-level noise from a pump will be found annoying under these conditions. The conclusion is that even if an automotive water pump has a simple functionality and the technology basically is more or less to be treated as a commodity there will be high requirements on the performance that are even higher than for today's mechanical solution.

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Soft-magnetic composites (SMC) components are very similar to PM sinter parts regarding the processing of core components and they can be effectively produced in large volumes to meet the demands of the automotive markets very well. The major competitor to SMC is still punched and laminated steel stacks [1], that are produced in huge quantities at the lowest cost. On the other hand, this competition is actually not about replacing a laminated steel stack with a SMC component by direct conversion. This will be a direct waste since SMC have the advantage of operating in 3-dim compared to 2-dim for the lamination stack. This must be utilized by adapting the entire design otherwise the SMC will directly lose one of its major advantages. It's then very important to understand and consider the full cost structure since more components than the magnetic core will actually be influenced, potentially reduced and simplified by the improved redesign for SMC.

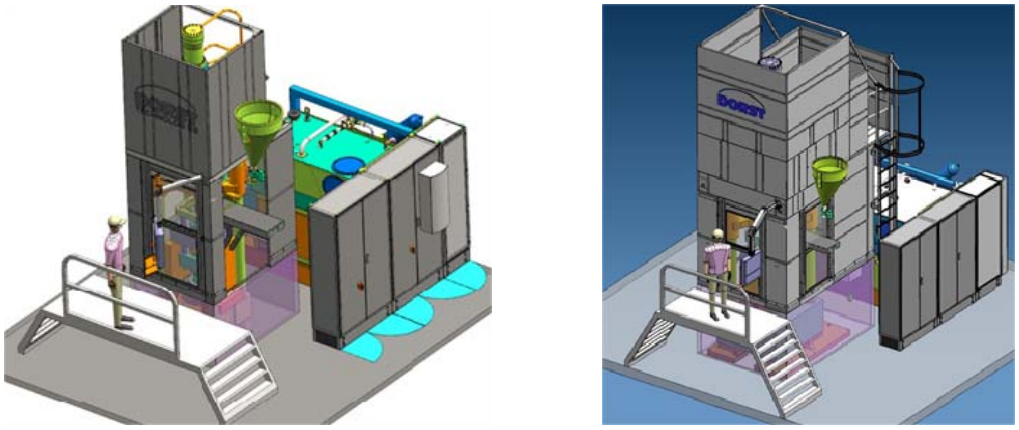
Power density (kW/kg) is an important measure to mirror the weight reduction of the electrical machine. The power is in practice the rotation speed times the torque which means it's possible to improve the power by either increase rotation speed, increase the torque or both at the same time. SMC can be used for both these alternatives since SMC have advantages in high-frequency operation that is the expected requirement from an increase of rotational speed. On the other hand torque can be increased by e.g. redesigning the typical inner-rotor radial flux machine into an axial flux machine (AFM) that will show a larger torque lever and thereby increase the torque at levels up to approx.25% without increasing the weight of the active components. The speed alternative must also be considered regarding the application, this may in turn result in the need of a gear-box to operate the application itself at an optimal speed. Usefulness of increased speed must therefore be judged on a case-by-case basis and does not automatically imply a given general solution. To change from radial flux to axial flux topology will result in a number of changes but all over the AFM will show less complexity and a range of simplifications if applied in a structured way.

This design and experimental study of a small automotive 50-100W electric auxiliary water pump is done together with acknowledged PM tool and PM press manufacturers. This confirms that the assumptions made for SMC component design and production are industrially feasible and indicate the required robustness and efficiency in production that will be required for large volume production. For the production of SMC components from powder, it will be beneficial to adapt the design of the powder press to the specific requirements, instead of using a universal press design. A review recently made by DORST Technologies resulted in solutions to cover the requirements with regard to the compacts geometry. The mainl points are:

- Single-level compacts of limited height
- Two-level compacts, often with a single level top punch (stators)
- Large area in a shelf die (up to more than 50% of the entire part face)
- Large centre hole
- Specific press force of 800MPa
- Typical press force approx. 3.500 kN / 5.500 kN / 7.500 kN

This converted into industrial machine design, resulting in:

- Single level type
- Reinforced hydraulics for die movement
- Adapted design of die cylinder with regard to force and travel
- Highly rigid core rod
- Design of 4.000 / 6.000 / 8.000 kN press force model



(a) (b)

Fig. 1. SMC-powder component press (ref. Dorst Technologies) a.) 4.000kN, b.) 8.000kN.

This focus to design a dedicated SMC powder press makes sure a user-friendly machine layout with a minimized footprint and even for large presses without pit. The CNC-closed loop control grants for closest tolerances, even during much larger production, and low energy consumption due to optimized dimensioning of the hydraulic elements. The well-known and mature system DVS/DCS® with the Intelligent Program Generator IPG® guarantee accustomed convenience in the setting and operation of the machine. The minimized movements allow a high output rate. Thus, this dedicated powder press model supports the part producer in their efforts to offer an economic alternative to the conventional production methods.

2. Experimental Procedure

2.1 The experimental automotive water pump concept and design

This study is based upon the specification of a small automotive water pump BLDC-motor [2,3] with 50W power. The specification based on appropriate market information and is presented here as a general example. The drive motor specification is shown in Table 1. The space-effective [4,5,6,7], axial-flux magnetic circuit is arranged in a similar way to the AFPM compressor drive examined in the study by Pompermaier et al [8]. The number of poles-slots is increased compared to the more standard 6-9 [9]. This will require some adaptions of the power electronics. In addition, the SMC component can be simplified geometrically for more cost-effective production.

Table 1. Motor design specification.

Parameter	**Value**	**Unit**
Nom. Power	**50**	W
Nom. Speed	**4000**	r.p.m
Nom. Torque	**0.12**	Nm
Efficiency target (pure electromagnetically)	**85**	%
DC-link voltage	**12**	V
Max. Current density	**5**	A/mm^2

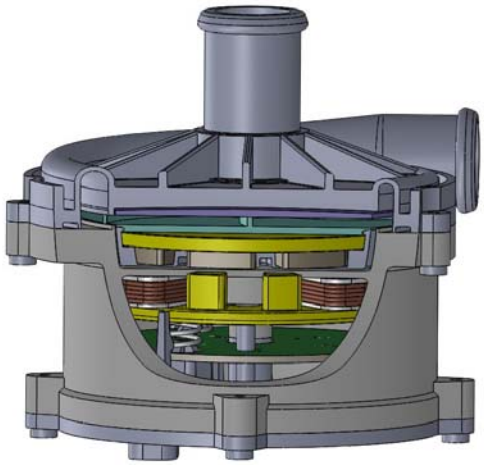


Fig. 2. Design study for a small 50W SMC automotive water pump. Axial-flux oriented, active SMC components are marked in yellow. The power electronics PCB is marked in green. The total axial length is not fully optimized in this illustration and may be substantially shortened after full design optimization.

Table 2. Motor design based on first design optimization.

Parameter	**Value**	**Unit**
Tooth / Pole no.	**12 / 10**	
Outer diam. incl. coil	**71.5**	mm
Inner diam. incl. coil	**32.5**	mm
Tot. axial length (magnetically active parts)	**18.8**	mm
Winding material	**Copper**	
Turns per coil (12pcs)	**14**	
Total coil weight	**31.4**	g
Permanent magnet material	**N48SH**	
Permanent magnet thickness	**4**	mm

Total permanent magnet weight	**51.4**	g

2.2 Manufacturing of experimental SMC components

The motor active soft-magnetic parts are designed for manufacturing. Corresponding industrial press-tools are constructed to demonstrate the technology as close to volume production as possible. The single-sided SMC stator component is described in Table 4 and the SMC rotor disk in Table 5. The tool sets shown in Figure 3 are designed and produced by Alvier AG PM-Technology, and are adapted for the Höganäs Somaloy® 700-series SMC powder material system.



Fig. 3. Tool-set for single-sided AFM SMC stator components.

Table 4. Experimental SMC stator processed at the Höganäs PoP-Center.

Parameter	**Value**	**Unit**
Stator material	**Somaloy® 700HR-5P**	
Stator outer diameter	**65.0**	mm
Stator inner diameter	**39.0**	mm
Stator axial length	**10.5**	mm
Stator weight / density	**92.8** **7.50**	g g/cm^3
Electric resistivity	**530**	µΩm
Max. µr	**580**	-
Hc	**125**	A/m



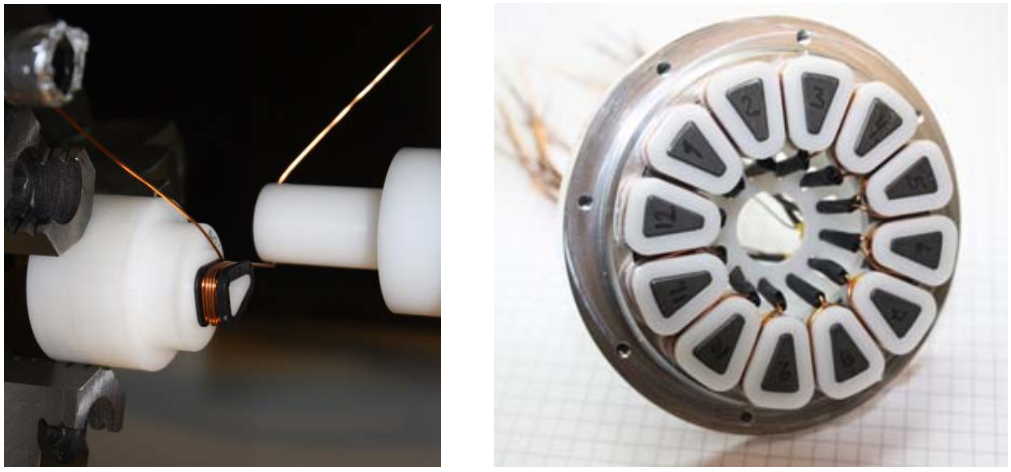
Table 5. Experimental SMC rotor-disk processed at Höganäs PoP-Center.

Parameter	**Value**	**Unit**
Rotor-disk material	**Somaloy® 700HR-1P**	
Rotor-disk outer diameter	**70,0**	mm
Rotor-disk inner diameter	**34,0**	mm
Rotor-disk axial length	**3,0**	mm
Rotor-disk weight / density	**53.3** **7.45**	g g/cm^3
Electric resistivity	**2300**	µΩm
Max. µr	**470**	-
Hc	**220**	A/m



2.3 Manufacturing of slip-on windings

The performance of the electric motor depends to a high extent on the electric coils. The coils for the AFM motor can be made dense, with a high copper fill-factor, since the winding process can be done separated from the stator core structure as shown in Figure 4a. This is a great advantage when compared to traditional laminated steel-sheet technology. The result is winding-bobbins that are easy to mount by simply sliding them on to the stator teeth. A further development could be to pre-mount all the coils in one structure together with the wiring assembly and arrange the connectors for easy mounting to the power-electric PCB board.



(a) (b)

Fig. 4. Simplified, high-precision bobin winding using circular insulated Cu-wire: a) Winding template set-up, b) Windings mounted on the SMC stator component in the experimental test-bench set-up.

2.4 Experimental test-rig for test of AFM SMC experimental motor

The validation of the motor performance was made in a special measurement rig that allows precision measurement of torque and losses. The active motor components are arranged in a fixture that is shown in Figure 5.

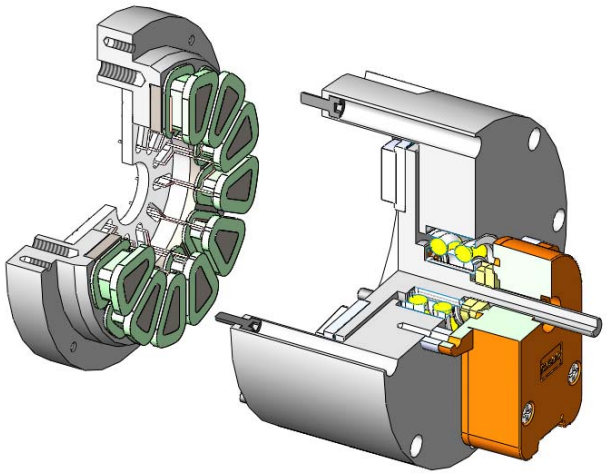


Fig. 5. Fixture for the axial-flux SMC motor. Stator to the left and rotor with shaft/bearings to the right. The orange device is an angular resolver for rotor position detection.

3. Results and Discussion

The results from the SMC water pump motor validation tests are presented here. Figure 6 shows the back-emf at a nominal speed of 4000 r.p.m. in comparison to the simulated results by FEA. The measured back-emf is in excess of the FEA simulation, which is positive. The deviation can possibly be the result of an in practice smaller air gap in the test fixture compared to the FEA model. However, this has not yet been verified. The good balance in between the three phases indicates good prototype quality, and the sinusoidal curve shape further indicates a beneficial condition for adaption of a standard power-electronic inverter.

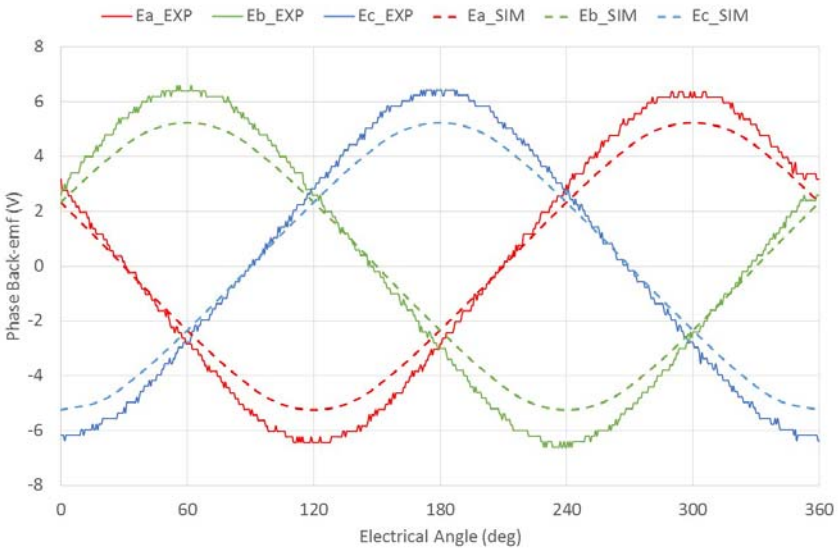


Fig. 6. Back-emf per phase, measurement results for the experimental SMC AFM motor.

Torque testing was conducted by applying a DC current to the q-axis of the motor and measuring the reaction torque produced at different rotor positions. The results presented in Figure 7 show a good correlation between simulation and measured torque, indicating that the motor will produce rated torque at rated current input.

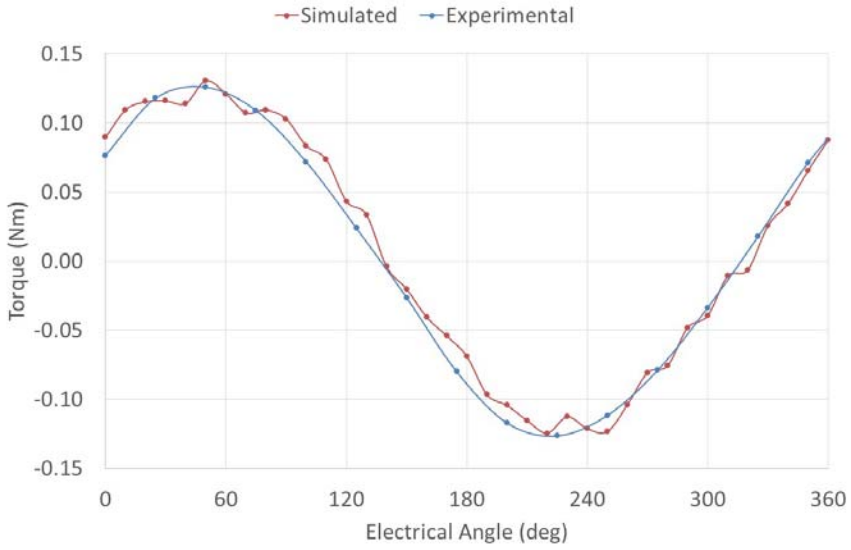


Fig. 7. DC torque measurement results for the experimental SMC AFM motor.

4. Conclusions

A design concept for a 50W automotive electric water pump was analyzed for validating the performance of an SMC-based axial-flux motor performance. The concept identified major improvements in:

- Simplification of the overall motor structure with a new AFM design-for-manufacturing approach
- Efficient production of net-shaped soft-magnetic SMC components
- Efficient copper coils with simplified winding process
- Compact motor package at very short axial length
- Efficient assembly of active parts

The design of the magnetic circuit was successfully validated in the experimental work. The SMC components manufactured by authentic industrial methods are experimentally verified and it can be concluded that the FEA design modeling results can provide a feasible, stable ground for practical SMC motor performance. The findings can most likely be utilized for other similar automotive cases e.g. transmission oil-pump, A/C compressor, fans etc.

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