Simulation driven development of a CFRPT gearbox housing

†Dr. T. Schneider[1], M. Kreutzmann[2], R. Rademacher[3], C. Dominé[4], H. Motte[5], *C. Tok[6]

[1]Technical Director ARRK/P+Z Engineering, Munich, Germany.
[2]Center of Competence Composite ARRK/P+Z Engineering, Munich, Germany.
[3]Powertrain department, ARRK/P+Z Engineering, Munich, Germany
[4]Low volume production department, ARRK/Shapers, France
[5]Low volume production department, ARRK/Shapers, France
[6]Crash department, ARRK/P+Z Engineering, Malaysia

*Presenting author: chyehock.tok@arrk-engineering.com
†Corresponding author: thomas.schneider@arrk-engineering.com

Abstract

To optimize the energy consumption of electric vehicles, the reduction of powertrain mass is important. Optimizing the weight of the typical two stage electric transmission is possible by substitution of the aluminum housing material with materials of lower density. Still, all requirements have to be fulfilled.

Carbon fiber reinforced thermoplastic materials provide a good combination of mechanical properties and fast manufacturing processes. The fulfilment of the necessary stiffness, especially at high temperatures of more than 100°C, is challenging for this group of materials. This resistance is important for durability and acoustics of the gearbox.

In this project, the housing material of an electric transmission, aluminum, is substituted by fiber reinforced thermoplastic material. An organo sheet (thermoplastic matrix) is over molded by a short fiber reinforced thermoplastic material. Aluminum inserts as bearing seats ensure to transmit the bearing loads into the organo sheet and reduce the deviation of the gear mesh. Additional injection molding ribs and UD-tapes ensure the stiffness requirements.

The morphological analysis investigated several concepts by using FE analyses and evaluated their feasibility. Topology optimizations, layer optimization and optimization of UD-Tape and injection molding ribs placement lead to load path optimized shape. Stamping and injection molding simulations were performed to optimize the manufacturability.

Close cooperation with the tool design ensures the manufacturability. The production of a prototype takes place in a three-phase process. In the first phase, the organo sheet and reinforcing UD-tapes are heated up, using an IR heating device and afterwards pressed in a stamping tool. Waterjet cutting produces the outline of the preform. During the final step, the organo sheet is heated again and over molded with the optimized rib geometry and all inserts to finalize the part.

Keywords: CFRPT, Gearbox housing material, hot pressing of organo sheet. Over molding of organo sheet

1. Leading motivation

Reduction of overall weight of the powertrain is one measures to reduce fuel consumption of vehicles. The weight of a gearbox housing can be reduced significantly by replacing the aluminum by a lighter material. Carbon fiber reinforced plastics with thermoset plastic matrices is suitable, as stiffness is one of the most important requirements for a gearbox housing. Unfortunately, the cost for this material is very high, compared to an aluminum cast part. Second, the production time is times 10-20 longer than the production of an aluminum casting part, what is a severe problem in mass production.

Injection molding and hot pressing of organo sheets are very cost effective. The process time is close to the process time in casting. Using organo sheets, carbon or glass fiber can be used in an orientated way in a plastic part, what provides stiffness to the part. In combination with thermoplastic over molding, any kind of geometry or functional detail can be added. The

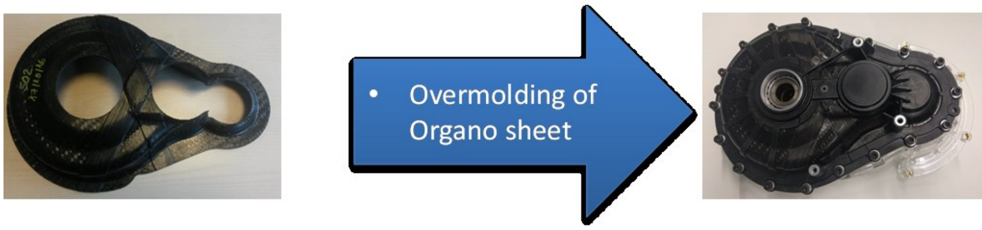


Figure 1: Over molding of organo sheet to introduce all relevant functions.

combination of both processes derive a part that has high stiffness and all necessary functional details.

As a demonstrator a gearbox housing used in an electric vehicle was chosen. The aim was to replace only the housing, all interior parts have been reused and work as proper as in the aluminum gearbox housing. The engineering approach used was simulation driven. Different types of simulations like finite element method, molding simulation, stamping simulation and optimization were used.

The companies ARRK P+Z, ARRK Shapers, ARRK SPG and ARRK UK were working together to show the ability of the ARRK product development group to develop the parts, to build the tools, to set up the production process and to produce in a small series production size. ARRK P+Z was responsible for the engineering, ARRK Shapers set up the production process, build the tools and the prototype.

2. Loads in the gearbox and simulation model

The gearbox used as basis of the project is sold by the company Getrag and used in the electric Smart. From the available data for the gearbox we derived the maximum torque of 130Nm at the input side for drive load case. With the given gear ratio, we derived an output torque of 1300Nm. For coast situation the torque depends mainly on the car weight and the car geometry. We derived a torque of 50Nm at the input shaft, which means a torque of 500Nm on the output shaft.
For the calculation of the torque load cases we imposed the loads on a simulation model. As drive and coast do not impose symmetrical forces into the gearbox housing, it is necessary to check both load cases in every step of the development. As the drive load case is more important for the optimization of the gearbox housing as the coast load case, the influence of

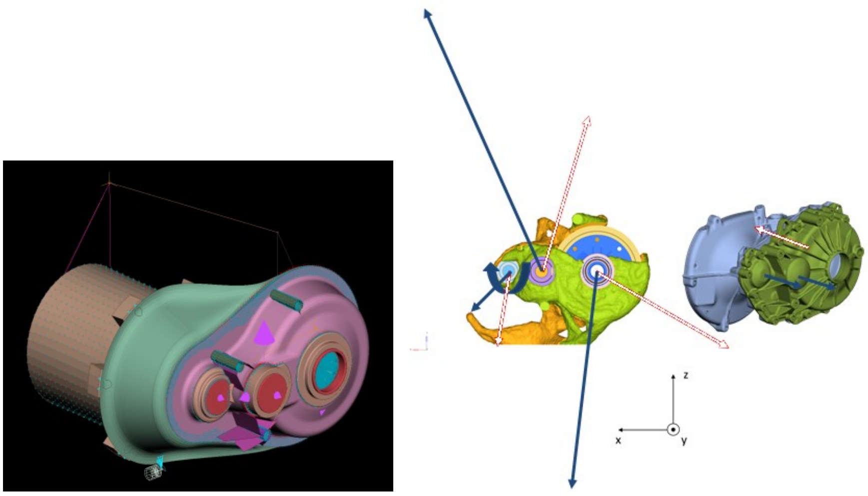


Figure 2: Left: Shell model of the gearbox (close to final design) with electric engine and fixation in the body. Model also includes internal parts like shafts and gears. Right: Qualitative radial and axial loads in the gearbox housing. Additionally a result of the topology optimization can be seen left hand.

the coast load case was not significant. We examined gravity load cases in x direction with 60g and z direction and 10g in x direction to simulate a crash situation and to examine the stability of the fixation of the gearbox to the car body.

To examine the impact of the torque load cases on the housing a model of the original gearbox with all the internal parts was build up. The geometry of the original gearbox was derived by disassembling the original gearbox and scanning the housing geometry.

3. Targets for the gearbox

The important performance targets for a gearbox are efficiency, lifetime and acoustics. The performance in acoustics is strongly coupled with the production of thermal energy, or the energy loss. A bad acoustic behavior, a short lifetime or generated thermal energy result in a low efficiency of the gearbox. In an ideal gearbox there would be no deformation of the housing by the transmitted loads. In such a gearbox, the tooth geometry could be designed for optimal efficiency [1].

Any displacement of bearings of the shafts leads to a change in position of the gears running on that shaft. Depending on the direction of the displacements, this leads to a misalignment of the gear mesh. The teeth of the gears compensate the deformation of the gearbox using e.g. crowning. The changes of the gears should be as small as possible to keep the efficiency of the gearbox as high as possible. Therefore the same stiffness values with the new housing material as in the original aluminum gearbox have to be reached. In terms of gear mesh, this means that the relative displacement between two shaft bearings have to be lower than in the aluminum gearbox. Axis deviation and axis inclination error of the intermediate and output shafts, have to be on the same level or below the values in the aluminum housing.

4. Material selection

The stiffness of the material depends on the kind of fibers and the matrix used. The glass fiber reinforced material showed about 50% of the stiffness of the carbon fiber reinforced material. Reaching the required stiffness was only possible by using carbon fiber reinforced material.
Equilibrated fabrics with 0°/90°/45°/-45°/-45°/45°/90°/0° stack were used and the thickness of the layers was optimized.
The organo sheet was available in thickness up to 5mm from the company TenCate. As thermoplastic molding material Grivory 40% fiber volume was chosen.

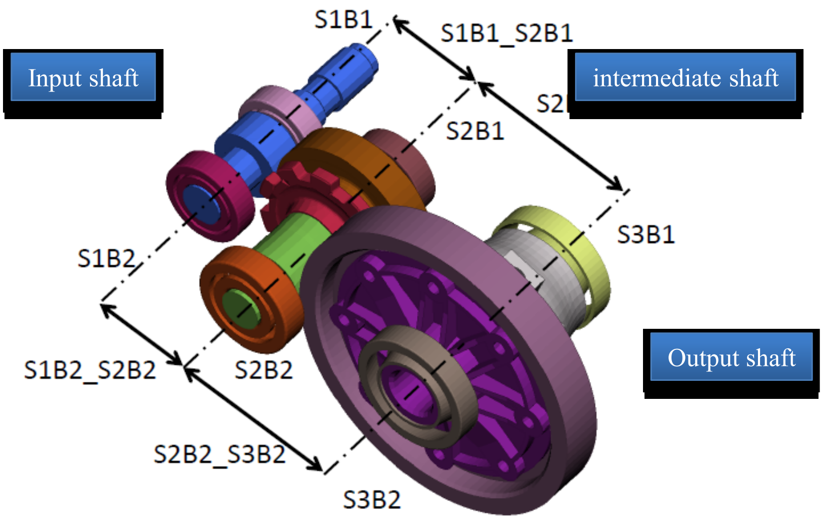


Figure 3: Declination errors occur between middle and output shaft of the gearbox.

5. Development of the gearbox

Concept phase

In the concept phase general feasibility was checked. The original gearbox housing was scanned and a FEA model was build up. Using this model we retrieved the following important results: Glass fiber showed a very low performance in stiffness, so we concentrated on carbon fiber for the organo sheet.

The housing part on the engine side was quiet stiff. Problems occurred from the part that we call the cover of the gearbox. Here, the most critical load case was the drive load case, and here it was the torsion of the gearbox that the cover could not prevent efficiently. The target value with the biggest impact on all decisions was the axis inclination between the intermediate and the output shaft.

The main parameters in the morphological box [2] for the gearbox were the following: Geometry, Loads, functional design, environmental topics, costs, maintenance. The three main concepts (five concepts were investigated) had the characteristics as can be seen in the figure 4. From the morphological analysis concept 1 and 3 were chosen.

Concept 1 offers the highest potential for weight saving and cost saving and the lowest production time. Concept 2 does not show the full potential of the thermoplastic fiber reinforced matrix material in combination with the carbon fibers. The metal link between the bearings covers all stiffness requirements. Concept 3 is a good compromise between concept 1 and 2 with cost and weight on a good level.

Design phase

Feasibility checks of concept 1 showed, that it is not possible to reach the necessary stiffness between intermediate and output shaft without using metal bearing seats. So we did not go on with concept 1 in the design phase and concentrated on concept 3.

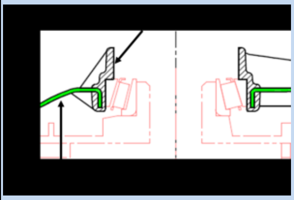
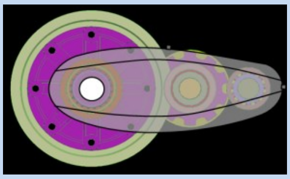
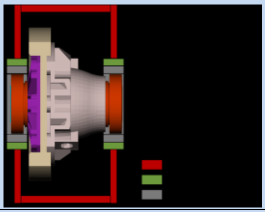
B6A1:B5A1:B4	1	2.1	3
Description	Low cost concept	Cage insert concept - GFK	Seperate bearing insert concpet
			
Details	- current gears, bearings, sealing - thermoplastic bearing seat - glass fiber organosheet - glued flanges (housing/cover) - no inserts at screws - center surface housing to cover - engine screwed to housing, centering by surface - simple air drain petcock with tube to avoid oil loss - air drain petcock also used for oil (re)fill - defined oil volume - smart lubrication concept - measuring oil temperature at oil	- current gears, bearings, sealing - connected insert for bearing seat - glass fiber organosheet - screwed flanges (hosuing/cover) - 2 inserts for each screw - dowel pin for housing/cover centering - engine screwed to housing, centering by surface - simple air drain petcock with tube to avoid oil loss - oil fill plug at maximaum oil level - smart lubrication concept - measuring oil temperature at oil drain plug	- current gears, bearings, sealing - metal insert for bearing seat - glass fiber organosheet - screwed flanges (hosuing/cover) - 2 inserts for each screw - dowel pin for housing/cover centering - engine screwed to housing, centering by surface - simple air drain petcock with tube to avoid oil loss - air drain petcock also used for oil (re)fill - smart lubrication concept - measuring oil temperature at oil drain plug - measuring bearing temperature at drilled holes

Figure 4: Final rating of the main three concepts investigated.

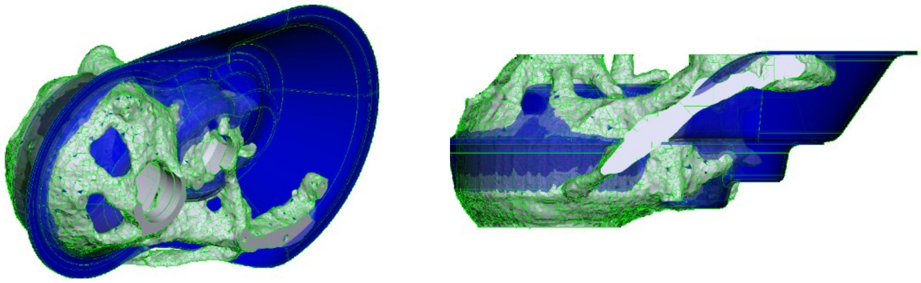


Figure 5: Results of topology optimization and derived geometry.

To derive a new housing geometry and a suitable fiber layout, optimization simulations were set up. The design space of the interior parts was designed due to the rules for gearbox housing design. In the topology optimization both load cases, drive and coast were used. Strain energy was optimized with weight, axis deviation and the axis inclination error as constraints. The main load paths for the stiffness performance of the gearbox housing were derived.

The optimization derived a geometry for both parts of the gearbox. This geometry was used to build up a simulation model for the detailed design. For all following simulations and optimization we concentrated on the cover. The constraints coming from production were already implemented in this design. These were mainly maximum steps in the cover, minimum radii and a maximum wall thickness of the organo sheet of 5mm.

After setting up this geometry, the layer thickness in the organo sheet was optimized. The optimization showed, that +- 45° layers should be the thickest ones. This is in good correlation with the fact, that the torsion in the housing is the main deformation causing the axis inclination error. As the stiffness derived from the optimization of the organo sheet was not satisfying, crossing UD Tapes and ribs were introduced into the geometry.

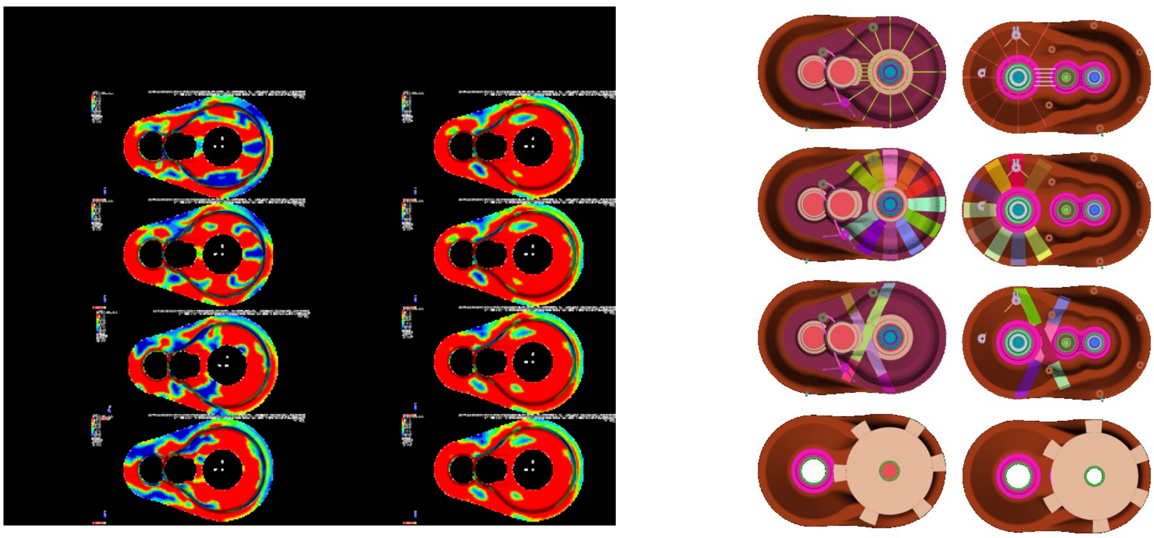


Figure 6: Left: Results of layer optimization. Right Different models for investigating crossing UD tapes.

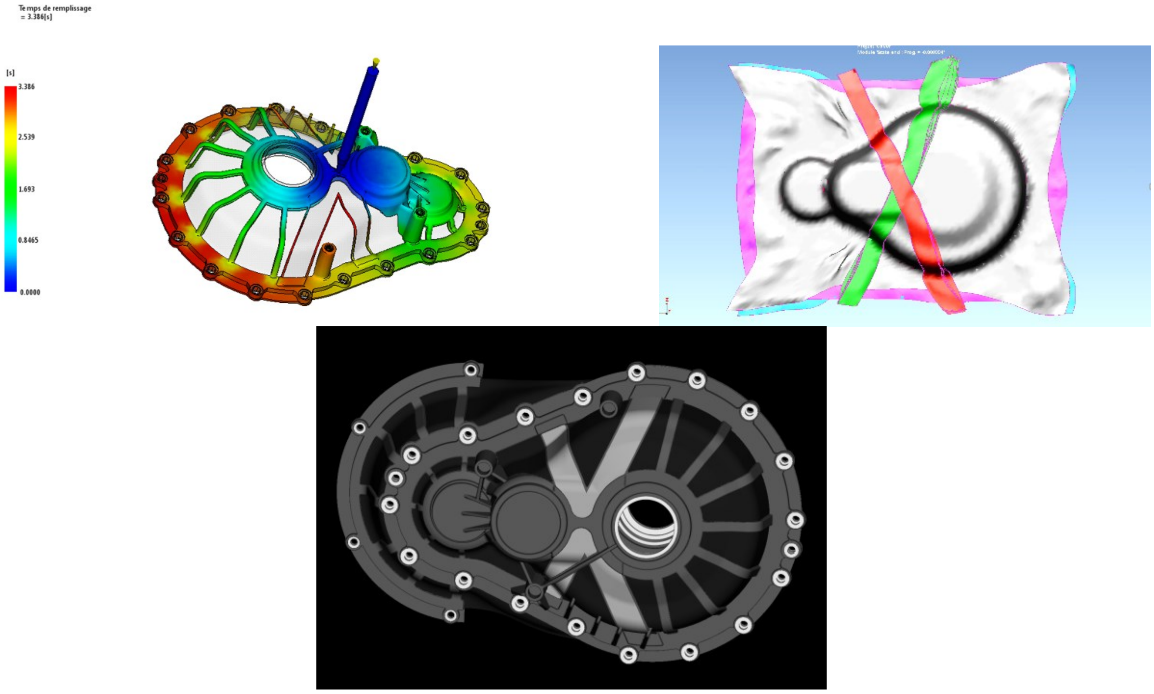


Figure 7: Top left: Simulation of over molding, top right: stamping simulation. Bottom: final design of the cover

Detailing phase:

The detailing phase added all details of functional fixing points and connections. For the connection of the two housing parts inserts were introduced. The flange, the centering pins and the functional faces have been detailed.

To make sure, not to have problems concerning the stamping process and to derive a starting cut for the raw organo sheet before stamping, a stamping simulation was performed with the help of the company ESI. To secure the overmoulding process a molding simulation was performed.

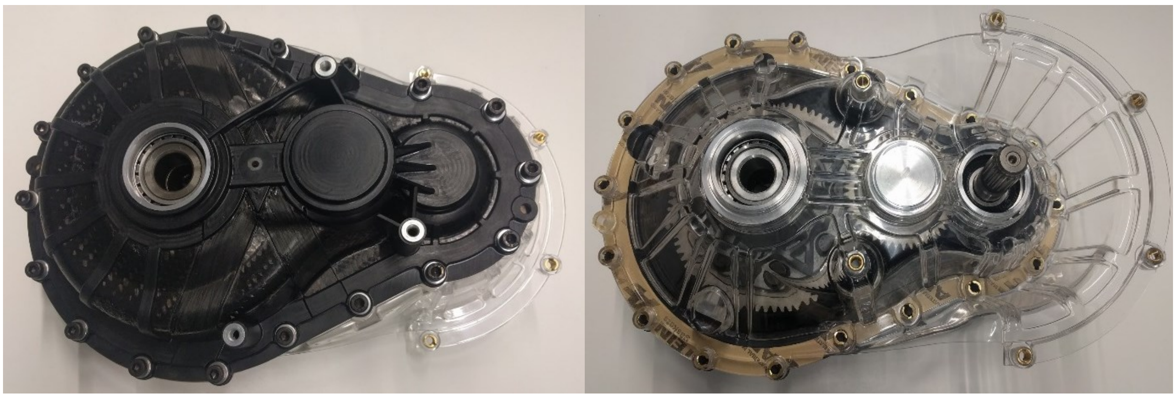


Figure 8: Finished and assembled prototype with PMMA part replacing the second housing part.

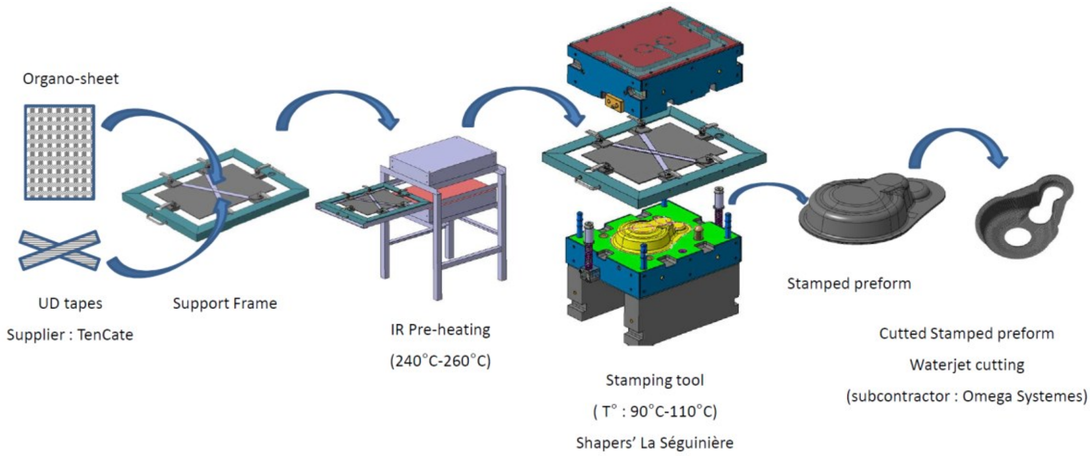


Figure 9: Production process for housing part.

6. Production of the prototype

The production of the prototype was done in four steps:

- Heating of the organo sheet together with the UD tapes using an IR heating device. Both components, organo sheet and UD tapes, are fixed in a frame that also keeps the UD tapes in the right position.
- Stamping of the heated organo sheet and UD tapes in a preheated stamping tool. After stamping, water cut to end shape.
- Overmoulding the pressed Organo sheet after heating the pressed Organo sheet. In the over molding step, the centering sleeves, the inserts for the screws and the bearing seats are inserted into the mold.
- Milling process of the flanges and the bearing seats to keep the required tolerances on the part.

7. Conclusion

Aluminum as material for a gearbox housing was successfully replaced by fiber reinforced thermoplastic material, CFRTP, with cross UD tapes stiffeners. After a milling step of the bearing seats, introduced in an over molding step, all tolerances are fulfilled. The performance of the gearbox cover is sufficient compared to the original aluminum gearbox. The results of the simulations show clearly that the torsional deformation of the gearbox is dominant in causing axis inclination errors. The feasibility of the production process and industrialization of the production was shown.

The weight achieved using the new material is 4kg compared to 5.8kg from the aluminum gearbox, what means about 30% saving. The cost of the cover was estimate between 50 and 80 Euro. The most expensive component is the organo sheet. The cycle time of pressing is about five seconds, the over molding is about 2 minutes. Water jet cutting can be removed by determining the stack outline in a way that after stamping no water jet cutting is necessary and the injection molding can take place at the same time.

The next step will be the production of the second half of the gearbox housing and stiffness measurements of the complete gearbox. Additionally organo sheet with PPA or PPS matrix will be introduced, what will lead to higher performance of the housing at high temperatures and reduced organo sheet thickness.

References

[1] Kissoft, (03/2016) User Manual. Bubikon, Switzerland
[2] Fritz Zwicky (1959): Morphologische Forschung. Winterthur, New. Glarus: Baeschlin, 1989