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COMPOSITE BRAKE DISC WITH STAMPED ALUMINIUM HUB – AN ULTRA LIGHTWEIGHT VARIANT FOR LUXURY AND SPORTS CARS

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ABSTRACT: Composite brake discs have become a state-of-the-art solution for mass reduction in the entire braking systems. Replacing a whole cast iron disc by a combination of a friction ring made of cast iron and a hub made of other material can lead to a lower total mass of the disc.

Aluminium is still one of the most desired materials for visible parts of brake systems – not only due to its low mass density. For luxury and sports cars, design and attractive look determine the purchasing decisions. Thus, the objective was to combine an attractively looking aluminium surface with a robust, safe and scalable concept applicable for luxury and sports cars.

The main challenge is to make the connection withstand the high temperatures and torques during abrupt braking events. Due to differences between thermal properties of cast iron and aluminium, disconnection of both parts in not the only problem the disc has to face. Different heat capacities and expansion coefficients can lead to unwanted restraints, dangerous above all for the hub which has to underlie an unnatural deformation – a possible reason for a pre-mature failure.

A cooperation of experts in metal forming and casting has become a base for a lightweight concept with a cast iron friction ring and a sheet metal hub made of aluminium. The concept has been tested by means of the FEM simulation and real dynamometer trials. The result is a robust design with minimised undesirable thermal and mechanical interaction between the hub and the ring.

The next phases of the project are the design optimisation and preparation for further performance tests, including trials in a real vehicle.

KEY WORDS: composite brake disc, aluminium brake disc hub, lightweight brake components, sport application, scalability

1. Introduction

Composite brake discs are currently a state-of-the-art solution – dividing the entire disc into the hub made of steel or aluminium and the friction ring still made of cast iron helps reducing the weight of the entire assembly and the whole brake itself. The concept is not new at all and there have been a lot of patents regarding this design submitted since the 1990's. Some of them, such as [1], are based on the inner part – also known as hub – made of sheet metal. The hub is joined to the friction ring by means of a forming technology, such as stamping. Since most of the ideas presented in [1] have never been implemented, one of them has become a basis for the so-called plug-in brake disc, the co-invention of Fritz Winter and Erdrich.

The plug-in brake disc has been presented on EuroBrake 2019 and described in [2]. The connection between the hub and the ring is made within a forming step so that a defined number of round locking pins is generated. The hub shown in Figure 1 is made of steel, with an initial sheet metal thickness of 2.5 mm.

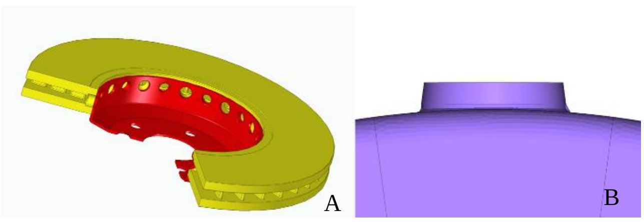

Figure 1 Geometry of the plug-in brake disc with the steel hub: A section view of an example assembly; B detailed look at a single locking pin at the hub

This concept has been implemented and tested – the results can be seen in [2]. In all aspects the plug-in brake disc provided better performance than this known from conventional discs fully made of cast iron. Especially the thermal deformation test and the thermal crack resistance test ended with significantly better performance. The deflection in the plug-in disc after the thermal deformation test was 0.3 mm lower than in the conventional component. There were no cracks detected after 1 000 load cycles of the thermal crack resistance test, whereas the serial disc ended the test with a fully penetrating crack after 350 cycles.

In the outlook of [2] some derivatives of the disc presented in the Figure 1 have been announced – since the plug-in concept is scalable, it is possible to apply it for multiple vehicle segments. There is also a need to find a suitable solution for sports and luxury cars, with an attractive look and convincing performance – the look and lower total mass are main aspects regarded by the sports and luxury cars' manufacturers. As a result, a concept with a hub made of aluminium has been created. In the first phase, the geometry of the friction ring remained identical as in the variant with a steel hub.

In this work the results of our research on the plug-in brake disc with a hub made of aluminium will be presented. The main principle of the connection remain unchanged – the material from the hub is pushed into the holes in the friction ring, stabilising the assembly in the radial and axial direction simultaneously. The performance will be compared to the conventional brake disc made of cast iron and the primary version of the plug-in brake disc with a steel hub.

2. Main properties of the new concept

The aluminium hub has been derived from the first plug-in brake disc design with a steel inner part. For the first try, the outer diameter of 198 mm and the height of the hub (48 mm) remained. The outer geometry of the initial hub has not been drastically changed. There are only two main differences – the initial sheet metal thickness has been increased from 2.5 to 5.0 mm and the openings in the cylindrical wall have been omitted. The selected material is EN AW 5754 (AlMg3), well-known and often applied at Erdrich e.g. in the manufacturing of housings for electronic automotive components. Due to lack of holes and higher thickness, the material deformation in the locking pins and the needed tool forces are expected to be significantly higher than in the steel hub. Both designs are compared in Figure 2.

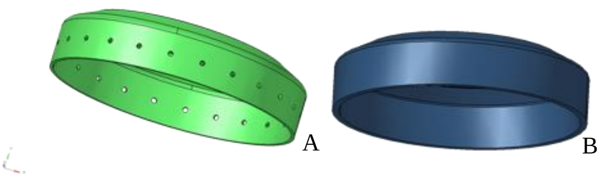

Figure 2 Comparison of the plug-in brake disc hubs: A steel hub with 2.5 mm material thickness; B aluminium hub with 5.0 mm material thickness

Since there was no change in the geometry of the friction ring between both plug-in variants, a direct mass comparison could be done. Although the volume of the aluminium hub is about twice higher, the mass density of this metal is more or less 2.9 times lower than in the case of steel. Thus, the aluminium hub has a mass of 640 g and is about 300 g lighter than its equivalent exclusively made of steel. The entire assembly has a total mass of 12.0 kg, whereas an assembly with a steel hub is 12.3 kg. The original part fully made of cast iron brings 12.8 kg into the braking system – all geometries are summarised in Figure 3.

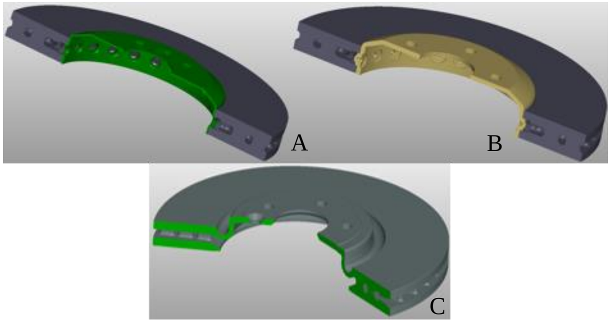

Figure 3 Comparison of the brake disc geometries: A plug-in with steel hub; B plug-in with aluminium hub; C conventional cast iron design

In order to simplify the comparison, the first variant created for the finite element simulation has got, if possible, the same parameters as the steel hub variant tested in 2019. This means, the number of locking pins and their diameter are identical to the already known and tested steel design – there are 24 pins with a diameter of 14 mm. In Figure 4 the expected geometries of the locking pins are presented – this is also the way they have been designed in the CAD software.

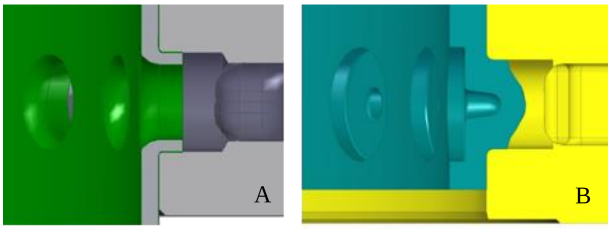

Figure 4 Locking pins in the plug-in brake discs: A steel hub; B aluminium hub

3. Finite element simulation

3.1. Methodology

As already mentioned, the main parameters of a new lightweight design have been taken over from the concept presented during EuroBrake 2019. The methodology of the finite element simulation has not been significantly changed either. However, there are some points that will be additionally observed in this research, namely the assembly simulation of the entire disc, inclusively the comparison to the steel variant. In this part, mainly the tool forces needed to create the locking pins are to be compared.

In the literature, [3] described how to calculate the size and amount of gearing elements in a brake disc hub. After some modifications of those formulas and relationships, they could be used also for the round locking pins – this part has been already done in [2].

The product-orientated part of the finite element research consists in a mechanical misuse test and a thermo-mechanical trial. In the mechanical misuse test, the stability of the connection between the hub and the ring is tested, with an assumption that the hub is a weaker component. Thus, the friction ring is modelled as a rigid body, so that there is no deformation allowed in it. The friction ring is rotated, until the braking torque reaches its peak – this means, the failure load has been achieved.

In order to save the computation time, the cyclic symmetry of the entire disc has been used, so that only one segment of the hub has been modelled and meshed – see Figure 5. Since there are 24 locking pins, the number of elements needed to create the model has been reduced 24 times. The holes on the contact surface to the axle have been neglected and closed – they have no influence on the simulation results.

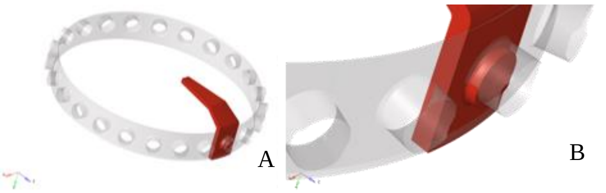

Figure 5 Example model to determinate the misuse braking torque of a plug-in assembly: A general overview; B detailed view on a locking pin

It is estimated that the braking torque in the passenger cars never exceeds 5 000 Nm. However, due to the lack of thermal influence in this simulation, a safety factor of at least 2 has to be respected – it means, the plastic deformation of the hub shall not begin before reaching 10 000 Nm braking torque. The results can be compared to the previously made misuse test on a steel hub.

The thermo-mechanical trial comprises two stages. In the first one, the transient temperature distribution during the test is determined. The trial itself is defined for three brake pedal actuations within 1 000 seconds. During the entire cycle, the connection in the assembly has to remain stable and there should be no plastic deformation in the contact zone.

Since there are results available from the finite element simulations of a steel hub, a parameter study of the aluminium hub has been reduced in the initial phase and postponed into the next research and prototype phases. As soon as the first prototypes are done and tested, some optimisation steps for the hub geometry can be applied.

3.2. Results

The mechanical misuse test has resulted with a very stable behaviour with a failure at the hub bottom – this means, the connection is stronger than the own torsion strength of the bottom of the hub. This was also a good indicator during the finite element simulation of the steel hub.

In Figure 6 a comparison of torque – angle curves for steel and aluminium hubs has been shown. DD13 and AlMg3 have similar yield strength values – therefore the curves are situated close to each other. However, the elastic behaviour of both variants is drastically different. While the elastic stiffness area of the DD13 hub ends at about 13 kNm, in the aluminium hub it exceeds 20 kNm.

The reason for this behaviour is probably lack of openings in the aluminium hub – it brings more stiffness into the assembly.

After 10 degrees of rotation, none of three compared discs has reached its failure torque – it can be clearly seen in Figure 6. The aluminium hub approaches about 30 kNm – in combination with more than 20 kNm of elastic area it is a safe, reasonable behaviour. The DD13 hub seems to have a higher failure torque – it is estimated at about 32 kNm, but the plastic deformation of the entire assembly begins earlier than using the aluminium hub. If we take a material with a twice higher yield stress – such as S420MC – the failure torque gets higher than 40 kNm. However, the elastic area is similar to this provided by the aluminium hub.

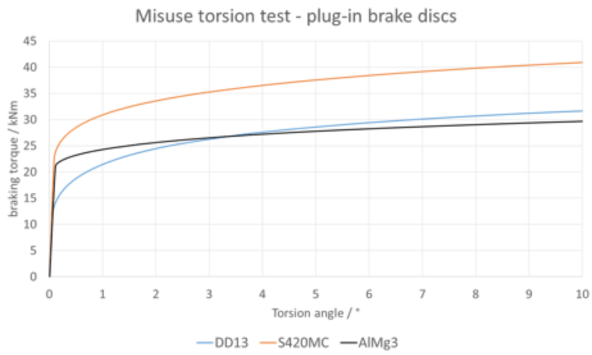

Figure 6 Torque – angle diagram for the misuse test of plug-in brake discs

Within the thermo-mechanical trial, first the temperature distribution has been determined. The temperature at the surface of the friction ring has not significantly changed after replacing the steel hub by an aluminium part – the maximum temperatures on the surface of the friction ring oscillate around 1 000 °C, which can be seen in Figure 7. As it could be expected, differences have been detected in the temperature distribution in the hub. The maximum temperature measured at the steel hub equalled 665 °C, at the aluminium hub it was only 459 °C. The temperature distribution in Figure 8 is presented for the same time point as in Figure 7 – it is the time point with the maximum thermal loading for the assembly, but not for the hub. This explains the difference between the values given above and visible in the contour plots.

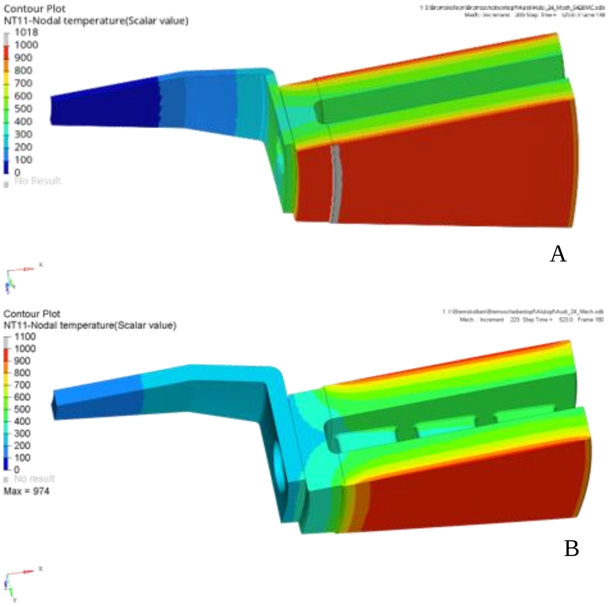

Figure 7 Temperature distribution in the time point of the highest thermal loading: A assembly with steel hub; B assembly with aluminium hub

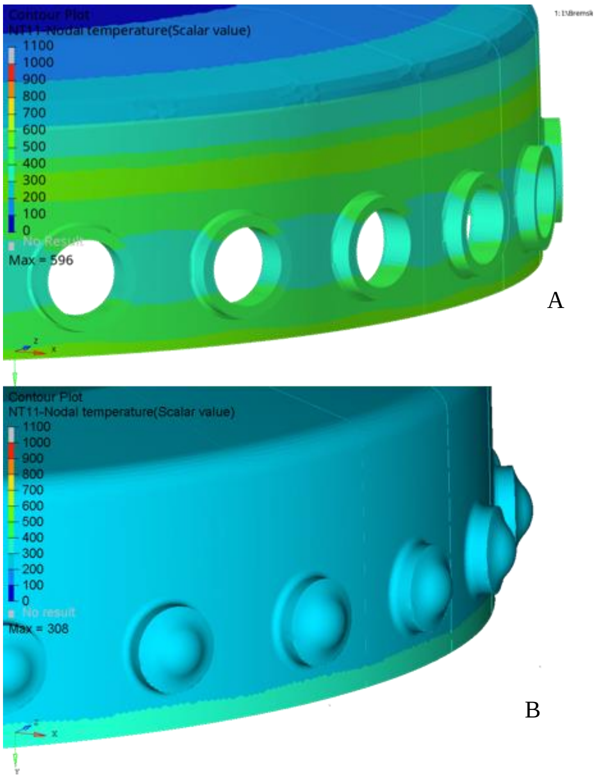

Figure 8 Temperature distribution on the hub in the time point of the highest thermal loading: A steel hub; B aluminium hub

The above-mentioned time point has been also observed in the thermo-mechanical loading step. There was no difference detected between steel and aluminium hub – see Figure 9.

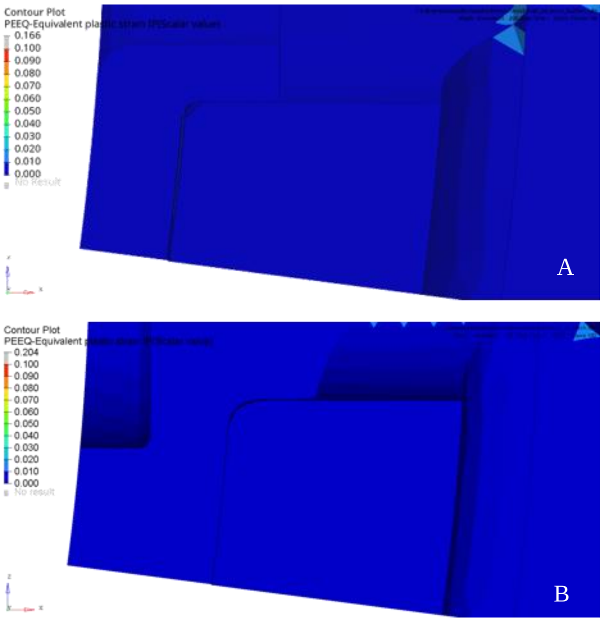

Figure 9 Detailed view on the locking pin at the time point of highest thermal loading: A assembly with steel hub; B assembly with aluminium hub

The gap between the hub and the friction ring has been observed during the entire loading time. In the cooling phase at the end of the simulation, the gap at the assembly with an aluminium hub increased up to about 0.45 mm. This phenomenon could be explained with a larger difference between the thermal properties of aluminium and cast iron than steel and cast iron. The effect can be seen in Figure 10.

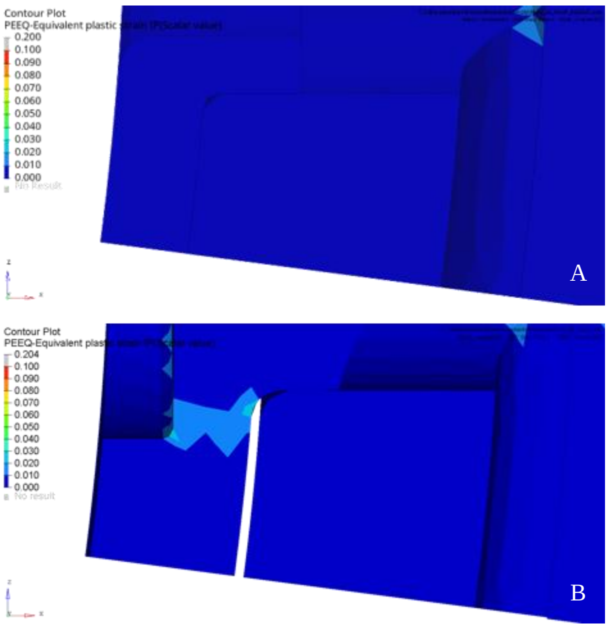

Figure 10 Detailed view on the locking pin at the end of the calculated loading cycle: A assembly with steel hub; B assembly with aluminium hub

This effect should be thoroughly observed and researched in all further analyses, including the prototype phase. At this time, it is not seen as critical. It has not been defined as a reason to interrupt the analyses and run optimisation loops until the gap is minimised. After a test rig trial, the gap will be measured at the real assembly and the behaviour of the entire assembly will be evaluated.

3.3. Forming simulation

From the manufacturing point of view, it is interesting to see the difference in the stamping force requirement between the steel and aluminium hub. Since there is a large deformation expected in the aluminium variant, it is not really suitable to perform the forming computation with a software used typically for the sheet metal forming simulation – even if we do not process a bulk material. Thus, the forging simulation software AFDEX has been chosen to research this topic – it is able to work with high deformations and has got a reasonable remeshing algorithm, so that the risk of interrupting the simulation due to convergence issues is relatively low.

The model setup in AFDEX is simple and the number of parameters determined by the user is limited to the necessary minimum, so that quick and reliable analyses can be done. In this forming simulation, the friction ring acts as a die – therefore, both friction ring and punch are modelled as rigid bodies. Although the software offers a possibility to compute the dies as elastic, it is not a suitable solution in this case. GJL-150 – the cast iron material used for the friction ring manufacturing – begins with the plastic deformation in an early phase, so that the Hooke's law does not apply. That makes the elastic die structural analysis much less meaningful. The elasto-plastic analysis of the friction ring during the forming process will be an object of further analyses for both steel and aluminium workpieces. The model setups for both workpieces are presented in Figure 11.

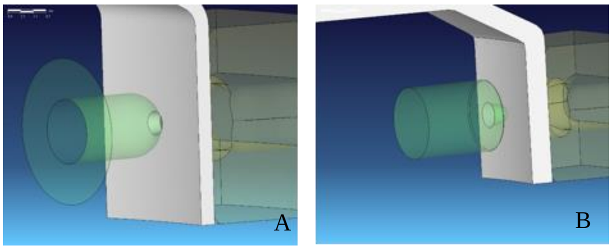

Figure 11 Model setup for the forming simulation: A steel hub; B aluminium hub

For both models, the plastic deformation resulting from the forming process has been plotted. The plastic deformation results in a work hardening effect which increases the local strength of the material. The plastic strain distribution in the aluminium hub is a bit irregular at the transition radii, which suggests a need to optimise this area – it can be seen in Figure 12.

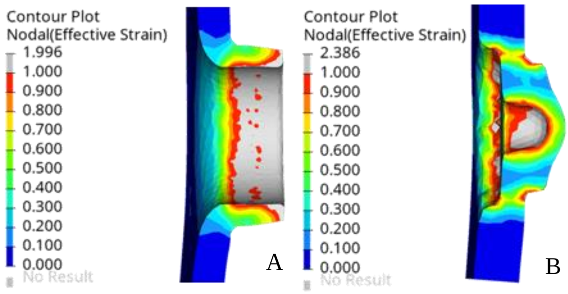

Figure 12 Plastic deformation resulting from the finite element forming simulation: A steel hub; B aluminium hub

However, the most important variable resulting from this analysis is the tool force. As it can be seen in Figure 13, the aluminium hub requires more than twice more punching force to perform the given forming process. There are a few explanations for this phenomenon. The aluminium hub has no openings in the cylindrical wall – that's why it needs more tooling force in the last phase of the forming process. Openings make the material flow freely until the end of the first phase of the forming process – after that, the force gets only lower. It is always harder to push out a full material, the deeper the more difficult. Another aspect is the material thickness - even if we compare steel to aluminium, the influence of the material thickness remains at least partially independent on the physical and mechanical material properties.

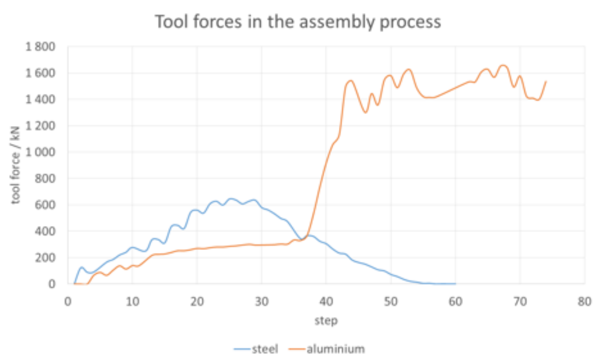

Figure 13 Tool force diagram for the forming simulation of the steel and aluminium hub

The results of the virtual analysis show that there is a need to research if the existing press shop is sufficient to assembly the brake discs with an aluminium hub. In case of too low press force, the locking pins can be insufficiently formed and the connection can easily get instable under harder test conditions.

4. Conclusion

The plug-in brake disc with an aluminium hub shall be an alternative design for sports and luxury cars. In those segments, performance is not the only key factor – a lightweight design and an attractive look are equally evaluated at the end. Replacing a steel hub by an aluminium hub reduces the total mass of the assembly by additional 300 g. Compared to the original one-part design made of cast iron, the difference is slightly lower than 1 kg.

The simulation results have proven that there is a possibility to create a composite brake disc in the plug-in design using a hub made of aluminium. After increasing the initial material thickness from 2.5 to 5.0 mm and omitting the openings in the cylindrical wall, sufficient stiffness against twisting is given.

In the thermo-mechanical part of the simulation, a gap between the hub and the friction ring increases in the cooling phase at the end of the loading cycle. This effect should be observed and evaluated in the phase of test rig trials.

5. Outlook

Basing on good simulation results, the plug-in brake disc with an aluminium hub has been approved into the prototype phase. The prototype assemblies will be manufactured within the next weeks or months and tested under the same conditions as the plug-in brake discs with steel hub. The results will be evaluated and compared to both conventional cast iron design and plug-in design with a steel hub.

If the first tests indicate potential for the future application, optimisation measures will be taken. The geometric and material parameters will be checked, parameter studies will be run in order to find the optimum form and setup of variable parameters in the assembly, such as the initial material thickness, diameter and number of locking pins or material strength. Since the design with an aluminium hub still will be scalable, another segments for potential applications can be found, e.g. small city cars from the higher segments, equipped with more powerful engines.

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