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HEAVY-DUTY APPLICATION OF A COMPOSITE BRAKE DISC IN PLUG-IN DESIGN

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ABSTRACT: In the heavy-duty application safety is always the most important factor – especially while designing brakes. There are a lot of legal regulations regarding the performance of the brakes in the commercial vehicles. Although mass reduction is rather a secondary topic, there is a lot of potential to exploit within the legally specified framework.

The maximum brake torques reach values that are a few times higher than those known from the passenger car industry. This implies application of more material – larger diameter of the friction ring, higher overall thickness of the disc and thicker hub. If a composite brake disc is considered, there is a special attention to be paid in the connection area – it has to withstand the extreme load cases determined by the extraordinary high total mass of the vehicle. Due to harder thermal conditions than in the passenger car industry, steel has been considered as the most appropriate material for the hub.

The plug-in concept of the brake disc comprises a scalable design applicable from small city cars up to heavy-duty commercial vehicles. It has already been tested on mid-class cars and received an approval for the spare part aftermarket. After scaling up, this concept appeared to be viable also for the hardest test and work conditions. An appropriate number of connecting points – called locking pins – and corresponding thickness of sheet metal applied in the hub lead to a robust form scalable for any kind of commercial vehicles.

Thanks to a unique cooperation between the members of different industries: sheet metal forming, casting and commercial vehicle manufacturing – a universal concept for heavy-duty applications can be presented. The first test provided reasonable results – the main values were not worse than those known from the discs mounted in today’s series trucks.

The concept is going to be optimised regarding mass and performance in order to assure that all the legal and technical requirements are met.

KEY WORDS: commercial vehicles, plug-in brake disc, heavy-duty brake components, cost-effective brakes for trucks, lightweight brake disc

1. Introduction

Commercial vehicles are a specific segment in the brake industry. The total mass of the vehicle is one of the factors that makes the difference in the dimensions of the entire brake system, including the discs, even if another parameters do not differ strongly from those known from the passenger car industry or are even lower.

The temperatures in the brake disc reach the maximum of about 600 °C in the extreme downhill tests, as well as on the test benches. This applies for both passenger cars and commercial vehicles. The requirements regarding the lifetime and braking torques are significantly higher in case of trucks. Every change of brake discs or brake pads means precious time spent in the service station – therefore it is desirable to reduce the number of exchanges to the necessary minimum (possibly one single change within 1 000 000 km is expected in the long haul driving). The upper value of braking torque is set at about 30 000 Nm, whereas the passenger car industry works with max. 5 000 Nm (6 000 Nm for BEVs). It should be noted that there is not a lot of space to increase the outer diameter of the disc – in the heavy-duty commercial vehicles, the discs’ diameters can be only about 50 mm larger than e.g. for the SUVs. Thus, there is no great potential to increase the contact surface of the disc with the brake pads this way. Other parameters have to be influenced.

The main difference can be seen in the total mass of the discs. If we compare a conventional brake disc fully made of cast iron (about 400 mm outer diameter) to a 22.5” commercial vehicle disc, the latter is about 2.5 to 3 times heavier. If we assume that at least three axles in the commercial vehicle should have brakes, only the six discs present in the system would possess a total mass of about 200 kg.

The plug-in design applies primarily for the discs with a hub having a form of a “pot”, as shown in Figure 1 B. As it can also be read in [1], there are two main ways the disc is mounted to the axle – the classic way with a “pot” and another one with an outer flange. This kind of design will be researched within this work. The feasibility of a plug in design for the variant shown in Figure 1 A has not been evaluated yet. It can be the next step of our research after a potentially successful application for the conventional “pot” hub known from the passenger car industry. Our experiences with this design was the main indication to begin with this type of disc geometry.

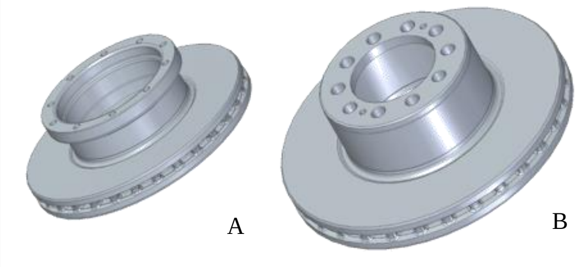

Figure 1 Brake disc designs available for commercial vehicles: A mounted at the outer flange; B conventional design with a “pot” hub

This work is a continuation of the research presented at EuroBrake 2019 [2], where a scalable concept of a brake disc applicable for most of vehicle segments has been presented.

2. Plug-in design

2.1. Main properties

Plug-in brake disc is a composite design with a friction ring made of cast iron and a hub made of another metal, such as steel or aluminium. The assembly succeeds by one or more metal forming steps, so that a number of connection spots – also called locking pins – is generated. There have already been patents with similar solutions, such as [3], but the solution shown in Figure 2 has never been applied in a real vehicle. A unique combination of expertise in iron casting and sheet metal forming led to an assembly which has already been tested and approved [2].

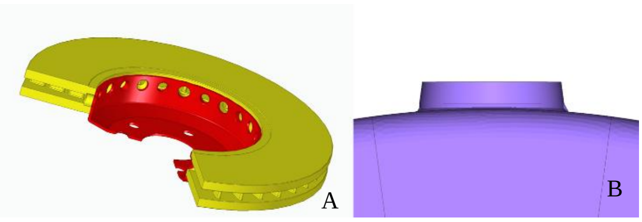

Figure 2 Geometry of a plug-in brake disc for a passenger car: A section view on the assembly; B detailed view on a single locking pin at the hub

2.2. Performance

The test rig trials provided results considered as better than those originating from the test of a conventional brake disc, fully made of cast iron. The plug-in brake disc with a steel hub performed better in the thermal deformation and crack resistance test than the disc currently mounted in series vehicles. The tests resulted with an ECE R90 approval for the spare part aftermarket [2].

One of the main advantages of the plug-in concept is its scalability. After varying the outer diameter, sheet metal thickness, amount and size of locking pins and a few other parameters, the concept can be applied for almost all vehicle segments, from small city cars to heavy-duty commercial vehicles.

2.3. Geometry for a 22.5” wheel

The concept has been scaled up to a dimensions corresponding to a commercial vehicle wheel with a diameter of 22.5”. The base model could be seen in Figure 1 B. The material thickness in the middle of the hub equals 16 mm and the entire cast iron disc has a total mass of 34.9 kg. Taking into account a supposed hub diameter of 256 mm and the height of about 144 mm, creating a plug-in design for this geometry could be challenging regarding the tool force needed and the dimension of the machine. The material thickness will definitely get close to the limits of steel formability – currently there is no chance given to an aluminium design for this purpose. In order to get a sufficient stiffness, S420MC has been chosen – this material has already been applied for a passenger car disc with an initial thickness of 2.5 mm. For the purpose described in this paper, this thickness has been doubled, so that the virtual analysis starts with a steel sheet of 5.0 mm thickness.

The next question was about the number of locking pins. Since there was no intention to drastically change the geometry of the friction ring, 15 and 30 appeared to be the most suitable numbers to design into the first models – so it can be assured that the cyclic symmetry is given for both parts of the assembly. Initial hubs for both quantities of openings can be seen in Figure 3, the section view of the assembly for 30 locking pins is presented in Figure 4. It can be seen that the round hubs connecting both sides of the friction ring correspond geometrically to the locking pins of the hub. The mass of the hub is estimated at about 5 kg, the total mass of the disc is going to be about 6 kg lower than the conventional design. Reducing the bottom thickness from 16 to 5 mm results in a reasonable mass saving, which can be converted into the payload.

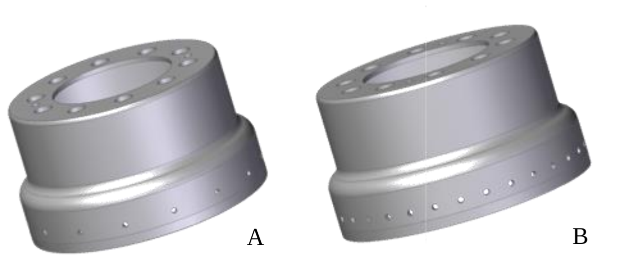

Figure 3 Initial geometry of the hub before forming into the friction ring: A 15 openings (future locking pins); B 30 openings

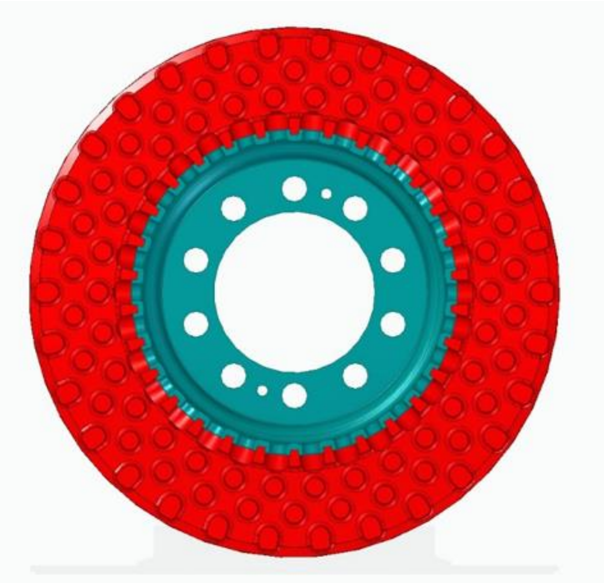

Figure 4 Section view of the entire assembly with 30 locking pins

Both variants are depicted in Figure 5. As it can be seen in Figure 5 B, if 30 connections are set, there is not a lot of space between the locking pins of 20 mm diameter. This region should be considered as especially vulnerable to crack initiation. In the variant with 15 locking pins, the diameter of each connection has been set to 22 mm, since it is assumed to strengthen the connection with this measure.

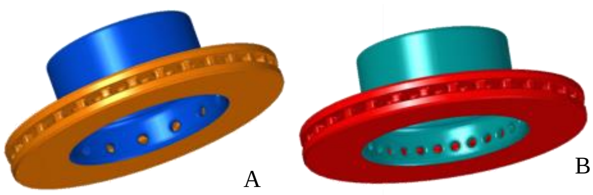

Figure 5 Plug-in assemblies for a heavy-duty commercial vehicle: A 15 locking pins; B 30 locking pins

3. Finite element simulation – strength

3.1. Mechanical misuse test

Since there was no former research which could give us an orientation about the expected strength of the assembly, the first parameter to find out was the resistance of the hub and the locking pins against twisting. It is supposed that the hub is a weaker part of this connection, more vulnerable to a deformation leading to the final failure of the assembly. The friction ring – as a more massive part – is defined as rigid body, where no deformation is allowed. Even if some cracks arised on the friction ring's surface, they would have no direct influence on the strength of the connection itself. Besides, the ring hardly experiences tension loading which could cause a serious damage in the system – in both forming simulation and mechanical misuse, compression is the main part of the load. Therefore, the model of the ring's contact surface is sufficient to complete the model.

The friction ring is rotated until the braking torque reaches its peak. At this analysis stage, no thermal loading has been defined yet, so that the failure loading will be determined for a cold material. Thus, it is necessary to work with sufficient safety factors.

This simulation has been carried out at the passenger car disc – the minimum required braking torque to withstand was 5 000 Nm, the considered plug-in disc had its peak at more than 40 000 Nm, whereas the elastic area of the torque-rotation curve ends at more than 20 000 Nm. Since the car brake disc performed extraordinarily well on the test rig, relatively similar results would be a good indicator, sufficient for an approval for prototype manufacturing. The minimum braking torque a commercial vehicle has to face equals 30 000 Nm. It is hard to expect that the elastic area of the curve will end at more than 120 000 Nm and the failure load will exceed 240 000 Nm. It is estimated that even 50% of those values will be sufficient to approve the component and start with the prototype manufacturing.

Another important aspect is the location of failure. The goal is to make the bottom of the hub fail and not the locking pins – the connection should be stronger than the hub itself.

As it can be seen in Figure 6, the model has been created using a cyclic symmetry condition in order to save the computation time. For the design with 15 locking pins, it means 15 times less elements, for 30 locking pins it is 30 times less. According to our prior tests on passenger car discs, all locking pins have to bear nearly the same load during the test, so that the braking torque is divided equally into the connections. There were no spots to show more wear, different kind of deformation or cracks on the circumference of the disc.

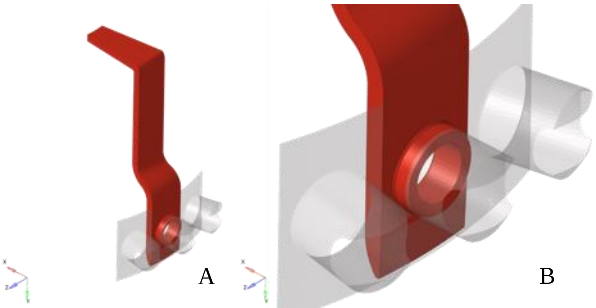

Figure 6 Example model to determinate the failure torque of an plug-in assembly: A general overview; B detailed view on a locking pin

As it can be seen in Figure 7, results for 15 and 30 locking pins significantly differ from each other. For 15 connections, the elastic limit is estimated at about 60 kNm and the failure load is about 96 kNm. Even if the elastic limit is equal to the minimum defined before, the failure load seems to be too low. Moreover, after having a look at Figure 8 A it is clear that the locking pin is the spot where the whole assembly fails, which is not desirable.

Increasing the number of connections to 30 and reducing the pin outer diameter to 20 mm leads to performance which is much more stable and provides better results. The elastic straight ends at about 90 kNm, the calculated failure load is 142 kNm. The location of the failure has been replaced to the high cylindrical wall – see Figure 8 B. This behaviour can be considered as equivalent to the bottom failure and thus acceptable, because the failing position is not the locking pin.

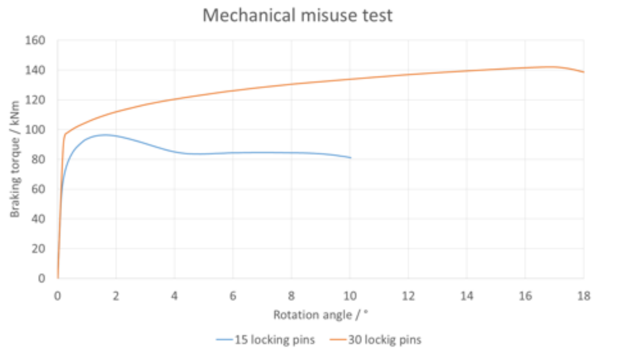

Figure 7 Torque – angle chart for the variants with 15 and 30 locking pins

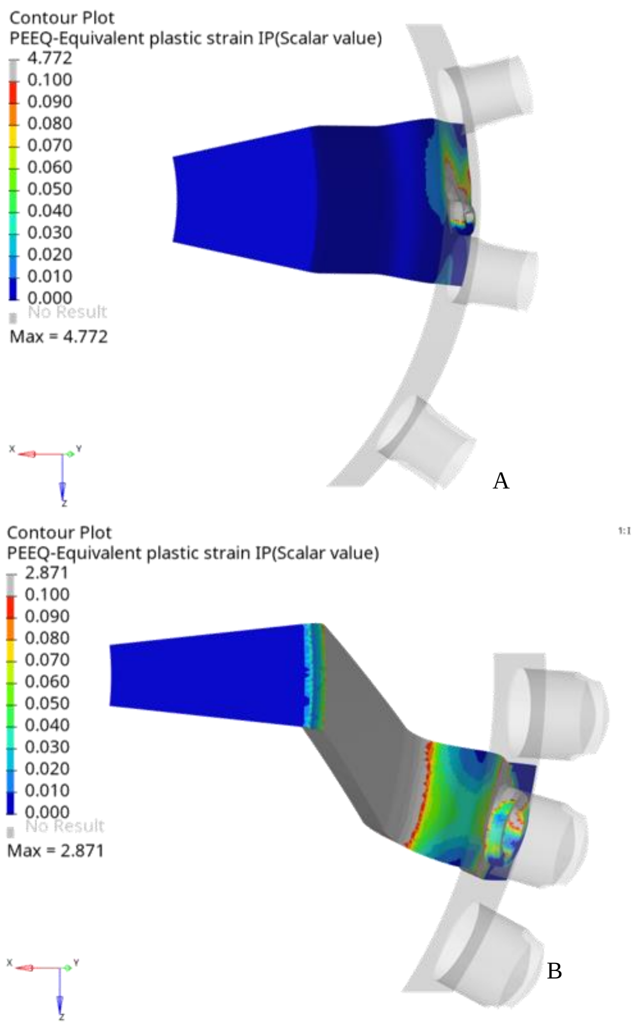

Figure 8 Failure location for plug-in designs: A 15 locking pins; B 30 locking pins

4. Feasibility analysis

4.1. Forming simulation

Since the design with 30 locking pins provided reasonable results, it was intended to check its mabufacturability. The CAD model of the hub is the ideal design, which can differ from the geometry received after a real forming process. Therefore, a metal forming simulation was carried out. Since the material thickness is relatively high, a typical sheet metal forming simulation could be insufficient to get utilizable results. Therefore, a forging simulation software AFDEX has been applied. The software offers a user-friendly interface with an easy modelling environment and leads to quick and reliable results – cyclic symmetry is applicable as well. In the feasibility analysis only one parameter has been additionally changed – the transition chamfer of about 0.5 mm has been replaced by a 2 mm fillet in order to avoid material damage on the friction ring's surface. This led to slightly worse performance in the misuse test, whose results will be presented in the further part of this work.

The forming simulation provided a maximum stamping force of 2 000 kN. It is almost three times higher than in the passenger car brake disc with a steel hub, but only about 20% higher than required for the aluminium hub. Therefore, the maximum tooling force does not seem to be a limiting factor in the manufacturing process of the hub. Only the height of the hub may require an additional investment in a stamping machine with more space inside, so that the available space is higher than 144 mm.

The model setup and results are presented in Figure 9.

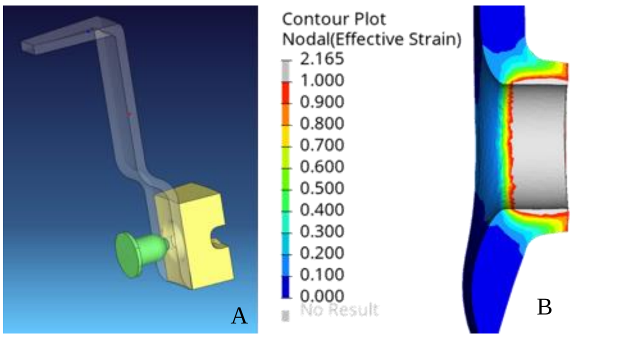

Figure 9 Forming simulation of the commercial vehicle brake disc: A model setup in AFDEX; B plastic deformation at the locking pin

4.2. Locking pin geometry

The locking pins have a few variable parameters which can influence the performance of the entire assembly. The range of admissible values of these parameters is mainly limited by the manufacturing restraints, such as minimum hole size for the punching process or maximum length of the cylindrical part of the pin that is manufacturable without macro-cracks.

The variability of the pins' diameter is limited by the material thickness and formability. Creation of a pin with less than 18 mm diameter is classified as unfeasible. The diameter of the initial hole in the hub must not be lower than the material thickness, otherwise it requires an additional, cost intensive processing step. In order to create a stable connection e.g. with a 16 mm pin, an initial hole diameter of about 1.8 mm would be required. The upper limit of the pin diameter is the space available between the pins. A diameter of 22 mm can already cause some stability and manufacturing problems because of the lack of cylindrical surface between the pins.

Moreover, a comparison between the misuse torques for diameters of 18, 20 and 22 mm leads to a conclusion that the best performance is provided by the second variant – this can be seen in Figure 10. Even if the results seem to be unambiguous, it is not easy to compare the variants to each other – each diameter lead to another initial hole diameter and locking pin height. The principal question is the definition of the criterion for the comparison. Either the geometries with identical initial hole diameters can be compared, or it could be done for variants with the same pin heights. Both parameters have a certain influence on the resulting failure torque**.**

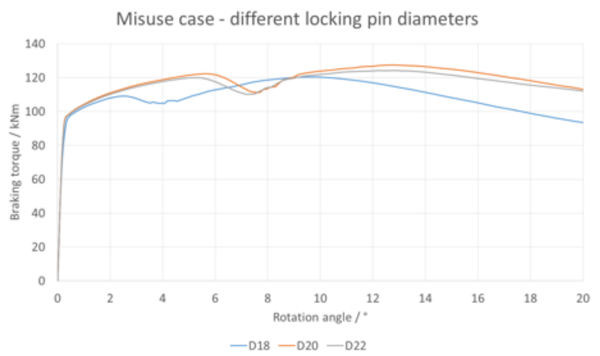

Figure 10 Torque – rotation curves in the misuse case for different locking pin diameters

However, the diameter does not influence the tooling forces strongly. Only the smaller diameter requires about 20% less force. The difference between the diameters of 20 and 22 mm is almost negligible – see Figure 11.

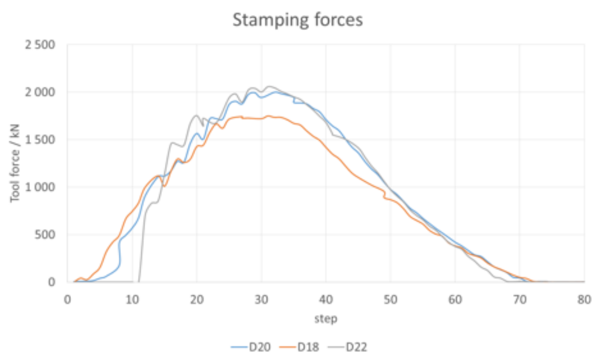

Figure 11 Comparison of the stamping forces required for different locking pin diameters

5. Conclusion

The plug-in brake disc is a concept that can be applied for commercial vehicles, including heavy-duty trucks. After replacing a conventional cast iron design by an assembly of a cast iron friction ring and a steel hub, a mass reduction of about 6 kg per disc can be achieved.

The first finite element simulations indicated that the hub with an initial material thickness of 5 mm should be able to withstand the brake torques appearing in the braking system of a heavy-duty commercial vehicle with a wheel diameter of 22.5”. The misuse test results are similar to those received in a similar calculation made for passenger cars.

According to the first analyses, feasibility of the assembly should be assured within a reasonable investment. Probably the most challenging part will be the height of the hub. The pressing machine should possess more than 144 mm of height inside the chamber. However, some geometrical parameters of the hub are restrained by manufacturing conditions. The pin diameter, height and number have strict upper and lower limits which must be respected.

6. Outlook

Further finite element analyses are planned to be carried out. The most important part will be the thermal analysis. An example test trial has to be defined, so that the heat transfer and braking torque progression in the timespan can be applied similarly to the simulation done for the passenger car discs. The resulting temperatures and thermal deformation have to be evaluated.

Furthermore, prototype manufacturing is going to start as soon as the best design has been defined. First test rig trials will give information if the direction which is currently taken is the right one. In the further steps, solutions for another wheel diameters could be found.

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