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CASTABILITY OF STEERING KNUCKLE FROM ALUMINIUM ALLOY BY LOW PRESSURE DIE CASTING REPLACING SAND CASTING OF CAST IRON

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Abstract: In this paper the manufacturability and useability of the steering knuckle which located at the front suspension system of mid commercial vehicles was investigated whether could be substituted from aluminium alloy by low pressure die casting method instead of conventional cast iron material with sand casting. In the detailed benchmark study, it has been observed that knuckles used in commercial vehicles generally made of cast iron material. Since lighter parts can be obtained with aluminum knuckle design it has been aimed to increase the load carrying capacity and also to achieve better fuel consumption. In addition, it is also intended to have better driving dynamics by reducing the unsprung mass and increasing the range for the electric vehicles. Primarily, both cast iron and aluminum knuckles were designed by following the related design rules. Subsequently, filling and solidification casting simulations were carried out to verify the relevant casting methods. In conclusion, strength and fatigue analyzes were carried out with the help of finite element methods to verify the structural suitability of the designs that have been made under similar vehicle loads before the prototype tooling phase.
Key words Steering knuckle, aluminium alloy, weight reduction, cast iron, sand casting, low pressure die casting.

1. INTRODUCTION

In the position where automotive industry is today; the useful load which also can be called as “payload” and vehicles dynamic behaviours like handling, comfort and manoeuvrability under this load has crucial impact for commercial vehicles especially in terms of maintaining the success in the related market share. That is the reason why big OEM’s who operates the global manufacturing and engineering activities consistently chase to optimize their existing components design from weight perspective for being more competitive and having better vehicle dynamics features.

In this study it has been investigated for mid-commercial vehicles whether the front suspension knuckle (wheel carrier) which has been conventionally producing so far with cast iron material and sand casting methode could be also producible with alumium alloy and low pressure die casting methode.

Within the scope of this study, more than 30 academic studies that may be beneficial and guide were examined. As a result of the examination, the details of three studies have been given that could be closest to the subject. Although there are some studies related with aluminum knuckles in passenger vehicles due to the fact that the total vehicle load is relatively lower than in commercial vehicles no study or research has been found about using aluminum knuckles for the medium commercial vehicles.

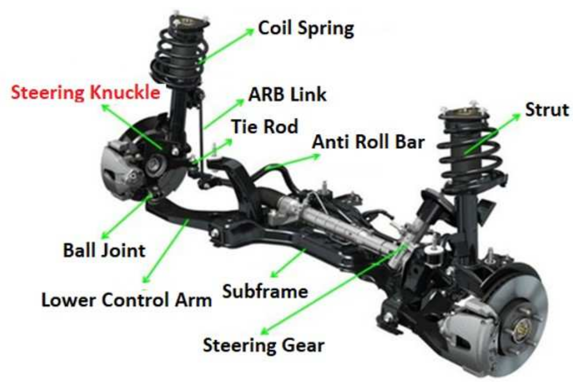

Fig. 1. Front McPherson suspension system

In this context, brief details about some of the studies that may be closest to this study have been shared below.

In the literature some researchers have been investigated the dynamic performance of the knuckles that made from different low density materials under the load cases of acceleration, braking, cornering, brake into pothole and drive over curb scenarios [1].

In another study researcher comparatively investigated what would be the structural strength of the steering knuckle if it has been obtained as a metal matrix (Al wt.10%TiC) from Al6061 alloy instead of conventional ductile cast iron.

Some researchers claimed that the knuckle, which also significantly contributes to the unsprung mass, should be lighter. In this manner stir casting method was tried to achieve a lighter steering knuckle instead of steel forging or casting [3].

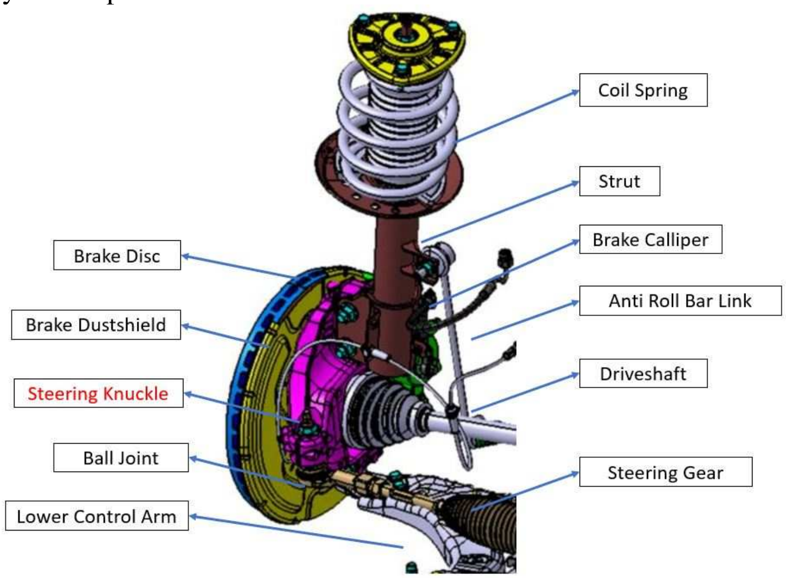

Fig. 2. Front steering knuckle interfaces

2. BENCHMARK / KNUCKLE DESIGN

In short, the vehicles that are specially produced and used for the purpose of transporting cargo, goods and passengers are called "Commercial Vehicles". These vehicles are classified according to their maximum laden weight as light, medium, and heavy.

2.1 Benchmark

Vehicles with a maximum laden weight of 3.5 tons and generally between 5.5 tons are called mid- commercial vehicles. The instrument group evaluated in this study also falls into this category. Some examples: Ford Transit, VW Crafter, Mercedes Sprinter, Fiat Ducato, Peugeot Boxer, etc.

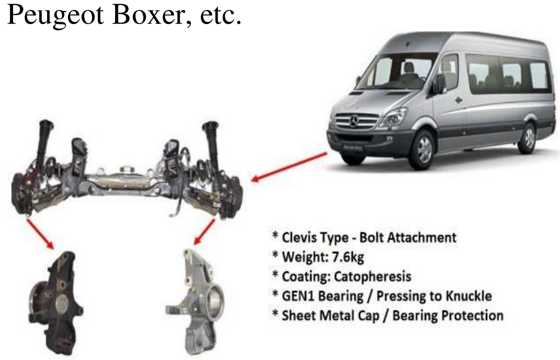

Fig. 3. Benchmark-1 knuckle details

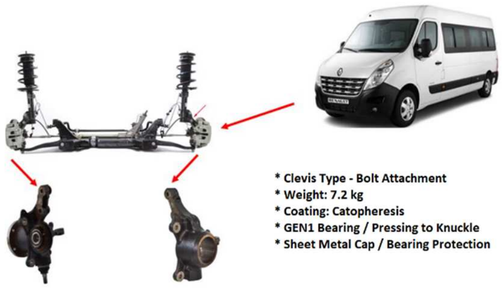

Fig. 4. Benchmark-2 knuckle details

Apart from this vehicles that details have been already given, the steering knuckles of other mid commercial vehicles were also investigated, and it was observed that they were also made from cast iron. No aluminum steering knuckle usage has been observed during the benchmark study.

2.2 Steering Knuckle Design

As stated before, the knuckle is one of the most critical structural parts of the suspension system in terms of its location and function on the vehicle. Therefore, it is necessary to ensure that all product development stages which needs to be considered during the development of a new project or part in the automotive industry are successfully implemented in a knuckle design to also make it suitable for mass production.
In this study, the following steps of general product development process have already been studied.

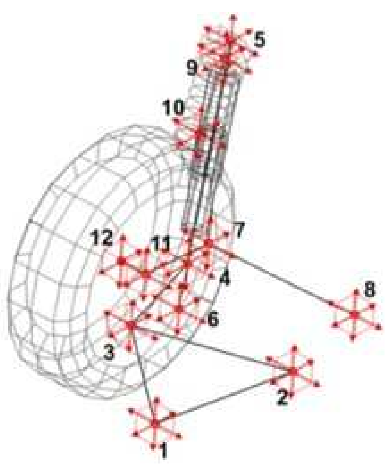

Fig. 5. Generic suspension hardpoints

- Cascading the determined vehicle level targets to chassis system level and then to component level. (Knuckle)
- Establishing the dynamic model of the vehicle in the virtual environment (Adams) and determining the suspension hardpoints.
- Clarification of the expected strength, stiffness, and corrosion targets from the knuckle after determination of the hardpoints.
- Determining the package boundary conditions that knuckle to take place.
- Designing the knuckle to be accordance with design rules and also vehicle engineering (NVH, Dynamic, Durability, Safety, etc.) targets.
- Examination of the knuckle design by the supplier in terms of tooling and process feasibility, considering the relevant production method.
- Updating the design, if necessary, according to the feedback from the supplier.
- Structural verification of the design with finite element methods.

The cast iron steering knuckle design was carried out with the help of Catia V5 design creation program by taking into consideration the related design rules, in accordance with the determined package area and the structural strength, collision safety, noise, handling and comfort targets determined by the vehicle engineering, using the sand casting method.

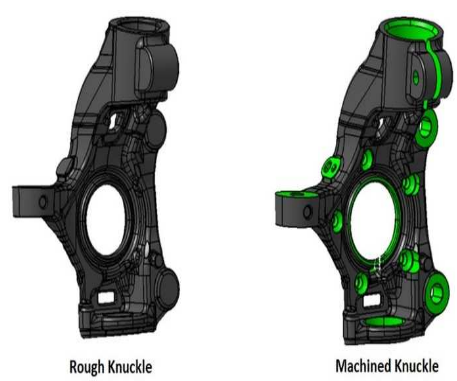

Fig. 6. Cast iron knuckle design

Table 1

Iron casting knuckle design details

Material	Weight (Kg)	Bearing Attachment	Coating
EN GJS 450-12	6.03	GEN3	KTL Cataphoresis

In the cast iron knuckle since the right and left knuckles have a symmetrical design both parts can be obtained simultaneously from a single tooling. At the same time, the positions of the runners and feeders were determined to get the most suitable filling and solidification results.
After determining the location of runners, needs to be decided that where the feeders to be placed considering the analysis which indicates the last solidified areas of the part.

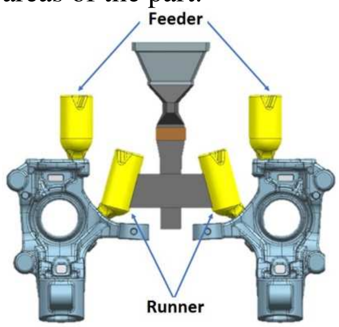

Fig. 7. Cast iron knuckle runner and feeder locations

The same product development stages mentioned in the cast iron knuckle design sections are also valid for aluminum knuckle design. Since the use of aluminum knuckle instead of cast iron is examined in this study, it is very important that both designs adapt to the suspension critical connection areas. Ideally, all critical attachment points would be expected to be the same for both designs for the dynamic performance of the vehicle, but the changes that could be also compensated by changing the design of surrounding components.
There are some design rules that must be followed while designing the knuckles. These rules emerge after many years of experience in the framework of component, system and vehicle level validation tests carried out during part development, as well as aftersales customer feedbacks.

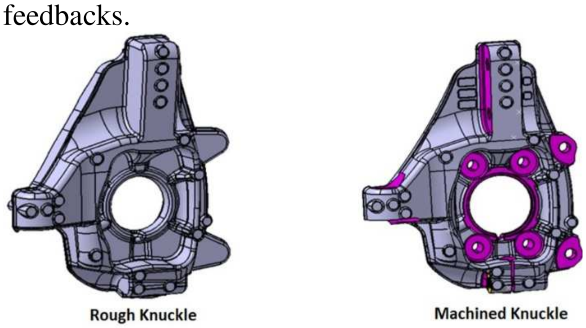

Fig. 8. Aluminium knuckle design

Table 2

Aluminium knuckle design details

Material	Weight (Kg)	Bearing Attachment	Coating
AlSi7Mg (A356 T6)	4.05	GEN3	No Coating

In the aluminum knuckle design, pushers are placed in the most suitable positions to come out of the casting on the part, slot, hole and stop points to be used for centering and reference during machining, as well as air filters. Pushers serve to separate the part from the mold after the process is complete. Air filters, on the other hand, allow the air inside to be evacuated out of the mold cavity while the liquid metal fills the mold cavity.

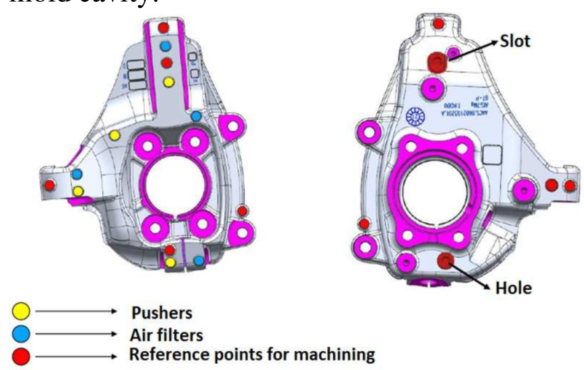

Fig. 9. Aluminium knuckle pusher, air filter locations

The low-pressure casting tooling made for the aluminium knuckle consist of tools called lower and upper, respectively, and the structural connection plates that connect them to the bench, the cooling group consisting of pipes that cool the mold, the connection plate with the pushers, and finally the plate to which the bench is connected. In this design, the core part is defined as the last cooling zone and the tooling design is made accordingly. It could be in more than one runner depending on the part geometry. In this design, the single runner in the core was sufficient to fill the mold. In order to cool the mold, cold water is at approximately 10 °C, free of lime, is passed through the pipes positioned between the tools according to the part design. As the part starts to solidify from the upper surface, the position of the cooling pipes is adjusted accordingly. The process of one part takes about 5 minutes.

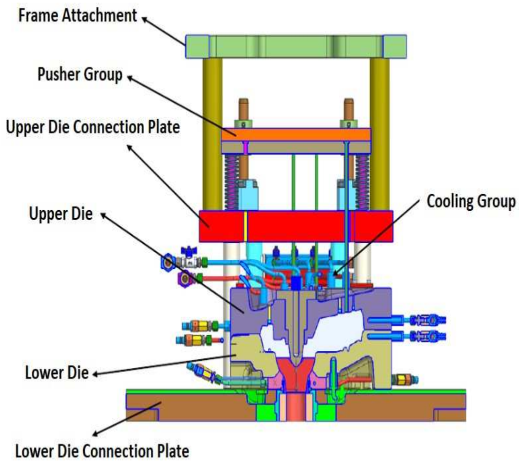

Fig. 10. Aluminium knuckle low pressure die casting bench

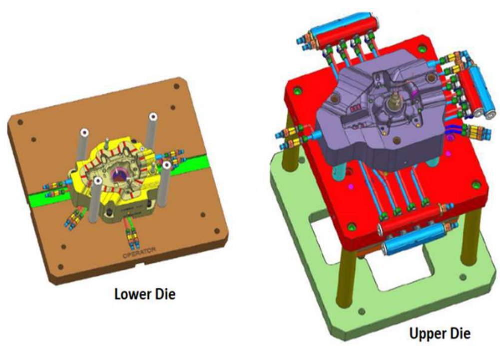

Fig. 11. Alumium knuckle die details

3. CASTING SIMULATIONS / METHOD VERIFICATION

After the knuckle designs are made, filling and solidification analyzes should be performed to check whether the design is suitable for the relevant casting method and, if necessary, to correct/optimize the design before prototype mold making. The simulation analyzes were carried out with the support of Magmasoft 5.4 software.

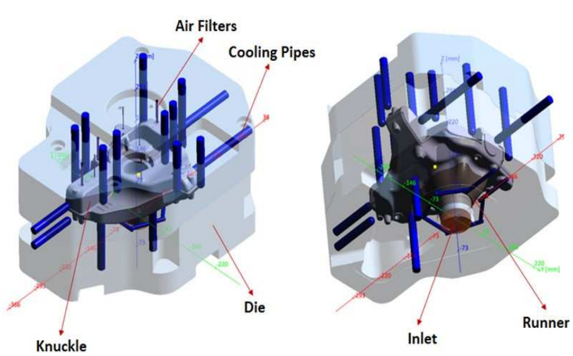

Fig. 12. Magmasoft 5.4 interface definition

- There are some steps needs to be followed in the program before starting the analysis. Briefly;
- First, rough CAD data of the knuckle is loaded into the program.
- The upper and lower dies, pushers, runner, air filters, cooling pipes, structural connection parts, etc are loaded into the program and defined accordingly.
- Air filter's location and material, refrigerant and with the help of the inlet command, it is defined where the melted metal enters the mold. (The runner is defined.)
- After all the definitions are completed, all the cad data called meshing is divided into much smaller pieces. While the elements that make up the mold are subjected to a coarser meshing, the casting part is meshed in a much more detailed way and consists of small cube particles.
- Afterwards, the mesh quality of the meshed parts is checked with the help of the program's automatic dividing into small particles command.
- After this process is completed, material entries are completed.
- Then, the molten liquid temperature, mold temperature, cooling water temperature and the heat transfer coefficients between them are defined.
- Parameters that are more related to the process, such as at what second the core is placed, if there is a core, and at what second the mold is closed, are also entered into the model.
- In order to start the filling, the definition of pressure inlet is also made, opening of the mold when solidification starts and as a side parameter, at which stage of the process the cooling water will enter and exit.

3.1 Filling Temperature and Speed Analysis

In the filling temperature analysis, the temperature changes during the progress of the molten metal in the mold cavity are investigated.

In cast iron knuckle analysis it is aimed that the molten metal temperature does not fall below the solid-liquid range of 1150-1200 °C as much as possible so that the relevant mold cavity filling process can be carried out properly. As can be seen in detail below, in the filling temperature analysis performed with the existing knuckle design, it was observed that the temperature was homogeneously distributed in every part of the part when the filling was completed and there was no risk of cold coalescence.

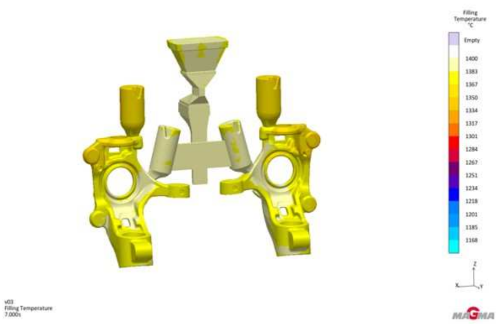

Fig. 13. Cast iron knuckle filling temperature analysis

In aluminum knuckle design similarly, in order to fill the tooling cavity properly, it is aimed that the material temperature does not fall below 613 °C, which is the solid-liquid interval of the material during the flow. It can be said that the filling process is suitable in terms of temperature values.

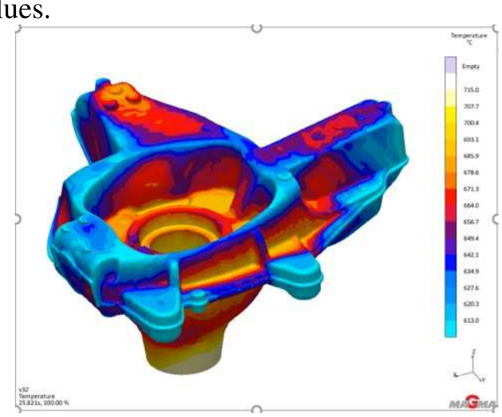

Fig. 14. Aluminum knuckle filling temperature analysis

The fact that the rate of filling the mold cavity of the molten metal is above a certain value creates risks such as agitation of the melt and trapping air spaces in it. This situation causes undesirable casting cavities in the cast part, which significantly reduces the part strength and adversely affects the quality of the part. It has been observed that the filling speed seen in the cast iron knuckle design, is around 0.7 m/s without causing any casting gap problem. This value should not exceed the 0.5m/s for the aluminum knuckle design as well.

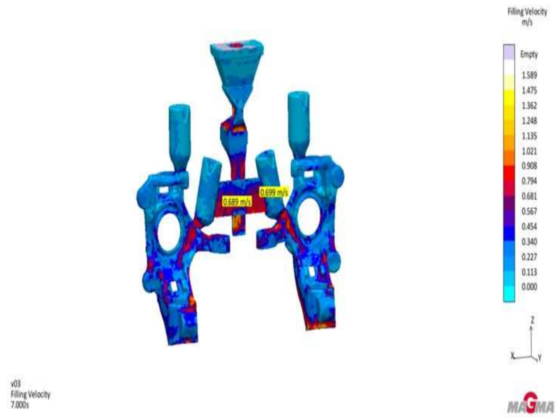

Fig. 15. Cast iron knuckle filling speed analysis

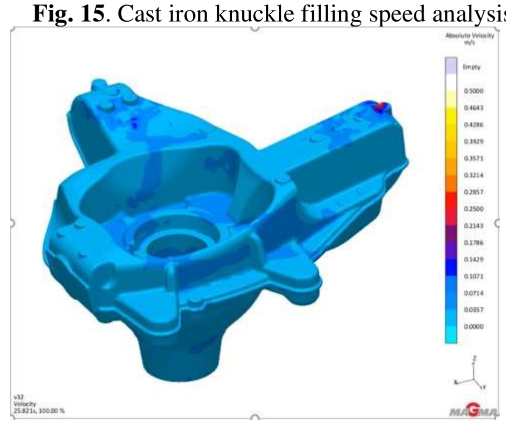

Fig. 16. Aluminum knuckle filling speed analysis

3.2 Solidification Percentage Analysis

The aim of this analysis is to examine the cooling form of the molten metal after filling the mold cavity and to have information about the general orientation of how the part solidifies. The most important point to be considered here is to make sure that the runner is the last solidified area, so that the feeding of the inner parts of the mold cavity during solidification is guaranteed. With the general solidification orientation information observed with this analysis, optimization can be achieved by intervening in the design if needed. For example, if the regions that cool down late are the regions of the part operating under critical load, solidification can be controlled by making a design change in these regions. In cast iron knuckle simulation, its observed that runners are the last solidified areas with existing design.

Fig. 17. Cast iron knuckle solidification analysis

Similarly, in an ideal solidification analysis in a low-pressure casting mold, the runner area should be the last solidified part of the part. In the simulation, it has been also seen that the last solidified region is the runner of the part.

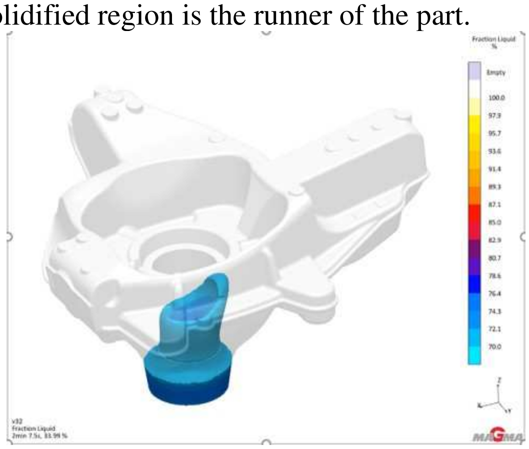

Fig. 18. Aluminium knuckle solidification analysis

4. STRUCTURAL ANALYSIS / DESIGN VALIDATION

Structural analyzes made with computer aided finite element method helps to decide about making prototype or serial tooling of the relevant design. As with many casting parts used in automotive, the tooling of the steering knuckle is also very costly.

Therefore, when OEMs are developing a new vehicle model, they collect road load data (force and moment) by running the vehicle on a special track over the existing model. The road load data collected on the relevant track is adjusted to simulate the entire life of the vehicle. Then, these road data which collected from the wheel center are cascaded to the system or part level. In this study, after the load values on the knuckle are determined, it is checked whether the design passes the analysis by using the relevant load values in computer aided finite element analysis.

Table 3

Cast iron/Aluminum knuckle properties [4],[5]

	Cast Iron	Aluminium
Material	EN GJS 450	AlSi7Mg
Tensile Strength (MPa)	310	288
Yield Strength (MPa)	450	234
Elasticity Module (MPa)	169000	72000
Elongation (%)	12	6

Since the knuckle is a part that is subjected to both static and dynamic loads, it is essential that many structural analyzes need to be completed before the proto tooling phase. In addition, in order to control the accuracy of the analysis, the results of the rig tests made with the physical parts obtained after the tooling process are compared with the analysis results, and the correlation levels of the analyzes determined.

As mentioned before, road load data is collected on a special track, both force and moment (X,Y,Z forces and Mx,My,Mz moments) from the wheel centers to be used in finite element analysis. Afterwards, these forces and moments are used as load inputs in CAE analyses, and it is aimed that the design remains within the structural boundary conditions under these loads.

In this context, the acceptance criteria required for both cast iron and aluminum knuckle designs to successfully continue the prototype tooling process have been determined as follows for both static and dynamic analyzes based on the experience and core engineering studies.

Table 4

Structural analysis acceptance criterias

Analysis Name	Acceptance Criteria
Camber and Toe Stiffness	Camber < 0.0454 deg/kN Toe < 0.44 deg/kN
Strength	Max. Plastic Deformation: (< %2.2) Brake Into Pothole: (< %2.2) Drive over Curb: (< %2.2)
Fatigue	Life: (>3)

4.1 Camber and Toe Stiffness Analysis

While the camber angle ensures that the vehicle turns corners safely, the toe angle prevents the vehicle from pulling to the right and left, especially when it is under load and propulsion. OEMs aim to keep such parameters within a certain spec when developing the vehicles. It means that the rigidity of the steering knuckle can be used in dynamic conditions such as driving on a straight road, braking, cornering, driving through bumps and potholes, etc. It should be at a level that will not exceed the previously determined camber and toe specs under the loads coming from the driving conditions.

With this analysis, it was checked whether the stiffness of the knuckle is within the spec from the road data by applying forces from the point where the wheel touches the ground. (Hardpoint 10).

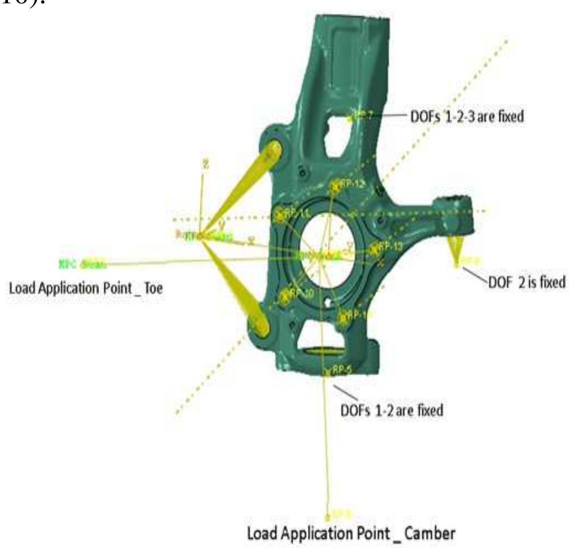

Fig. 19. Cast iron knuckle stiffness analysis boundary conditions

In the analysis of camber stiffness, a force was applied from the y-axis so that the critical point at which the wheel touches the ground is from HP10 to 5 kN, and how much the knuckle flexes is measured in degrees. In fact, the applied force from the HP10 created a moment at the wheel center. The vertical distance between the HP10 and the wheel center is the radius of the wheel.

In the toe stiffness analysis, a load of 2kN was applied from the y-axis at a distance of the radius from the wheel center (HP9), and how much the knuckle flexed in a similar way was checked.

Based on the analysis related results are given below, in the Table 5.

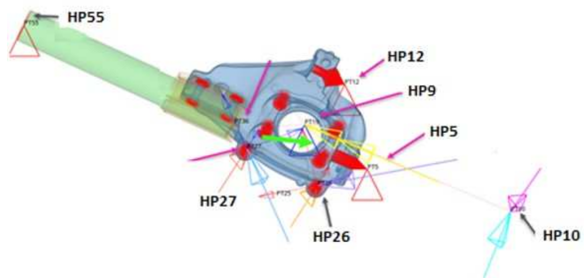

Fig. 20. Aluminium knuckle stiffness analysis boundary conditions

Table 5

Camber and Toe analysis results

	Acceptance Criteria	**Cast Iron Knuckle**	**Aluminium Knuckle**
Camber Stiffness	< 0.0454 deg/kN	0.0066 deg/kN	0.0452 deg/kN
Toe Stiffness	< 0.44 deg/kN	0.135 deg/kN	0.11 deg/kN

4.2 Strength Analysis

Another important analysis to validate the design is the strength analysis. With these analyzes, the forces and moments collected on a special track to simulate the different scenarios that may occur during the life of the vehicle, this time are applied to the whole of the knuckle rather than to a specific region, and it is checked whether the forces formed in the knuckle are below the yielding and breaking strengths of the part, especially under sudden shock loads are done. Especially in the scenarios of entering a hole while braking and passing over a bump, the plastic deformation that occurs in the part at sudden high loads on the knuckle must remain within the defined acceptance criteria.

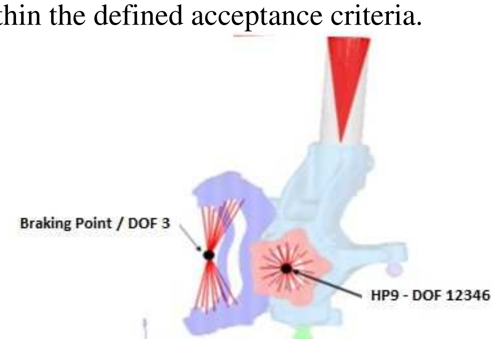

Fig. 21. Cast iron knuckle strength analysis boundary conditions

In this analysis, after the modelling is completed, the forces from the shock absorber (HP20), steering connection point (HP12) and ball joint connection point (HP6) are applied to the knuckle, and it is aimed that the strain value occurring in the part remains within the acceptance criteria. Load is applied from the specified critical points so that the knuckle is fixed from the center of the wheel, all the force and moment axes and the brake calliper connection points.

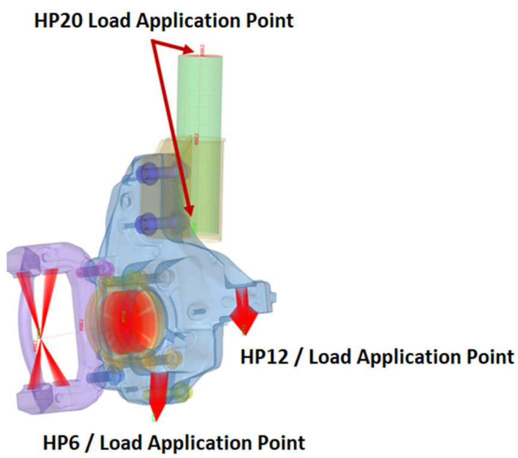

Fig. 22 Aluminium knuckle strength analysis boundary conditions

The load and moment table has been used according to the load scenario used in this analysis by cascading the vehicle level road load data to hardpoint level.
As a result of the analysis, it was observed that the strain values observed in the part according to both loading scenarios remained within the acceptance criteria.

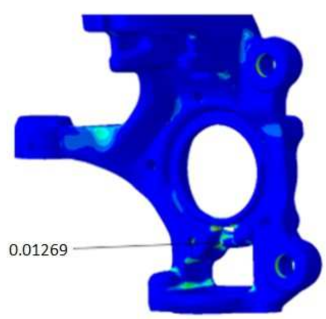

Fig. 23. Cast iron knuckle strength analysis result

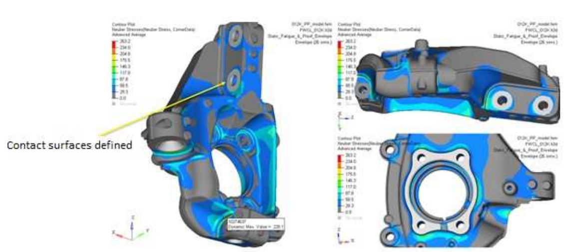

Fig. 24. Aluminium knuckle strength analysis result

It has been observed that the stress value seen in the analyzes made according to many different load scenarios, including passing over a bump and entering a pothole by braking, is lower than the yield strength of the part.

Table 6

Aluminium knuckle loading scenarios and results

Loading Scenario	**Acceptance Criteria (MPa)**	**Analysis Result (MPa)**	**Result**
Braking	234	104.2	OK
Reverse Braking	234	51	OK
Acceleration	234	60.8	OK
Reverse Acceleration	234	41.9	OK
Cornering RH	234	201.8	OK
Cornering LH	234	51.4	OK
Drive Over Curb	234	228.5	OK
Brake Into Pothole	234	231.9	OK

4.3 Fatigue Analysis

In order to analyze the fatigue resistance of the vehicle in dynamic road conditions, it was stated before that force and moment were collected from the wheel center in a special test track.
In this track, it is determined how many times the vehicle passes on which road condition. The multi-body dynamic model of the vehicle is set up in the Adams program. The force and moment values collected from the wheel center in the special test track are entered into this program, and the amount of loads for each knuckle hardpoint in the relevant road conditions is determined.
Afterwards, the knuckle is modelled in a similar way in the program in which the fatigue analysis will be performed. The boundary conditions and load application points in the fatigue analysis are the same as in the strength analysis, unlike the strength analysis, the collected road load data is given to the relevant hardpoints on the knuckle as fatigue data and it is checked how the part performs under these long-term loads.
The analysis is first done statically and the mechanical properties of the material (modulus of elasticity, density, Poisson ratio etc.) and fatigue curve are entered into the program

beforehand. Then, with the help of Adams model, the load and moment information obtained for each hardpoint from different road conditions are entered. As a next step, the analysis is run and the stress values on the part are determined.

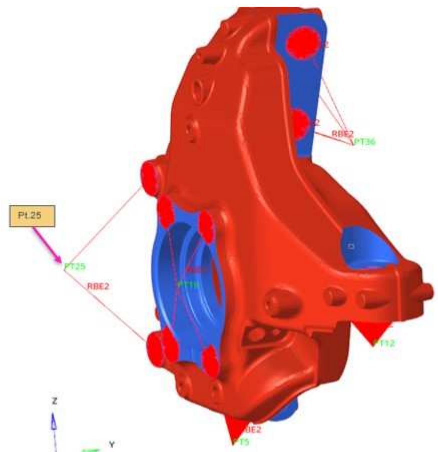

Fig. 25. Aluminium knuckle fatigue analysis boundary conditions

Before starting the actual dynamic fatigue analysis, the number of repetitions of each road condition is also given as input to the program. The total effect formed by the number of repetitions of the stress value obtained by static analysis creates the total fatigue stress value that may occur on the part. The resulting total fatigue value is compared with the fatigue curve and mechanical properties of the material, and it is revealed how many times the part can complete the relevant test track.

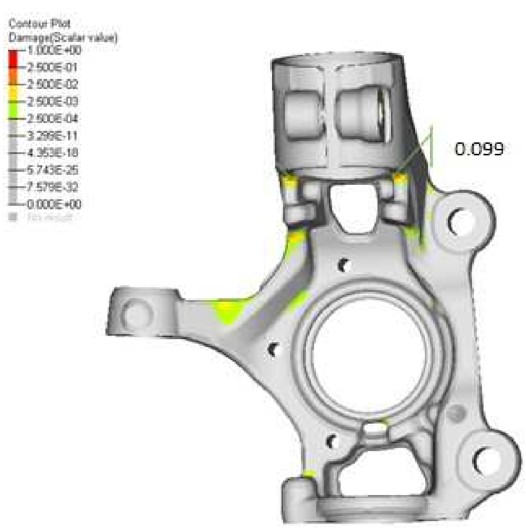

Fig. 26. Cast iron knuckle fatigue analysis results

Table 7

Cast iron and aluminium knuckle fatigue analysis result

	Acceptance Criteria	Result
Cast Iron Knuckle	>3	10.1
Aluminium Knuckle	>3	2.8

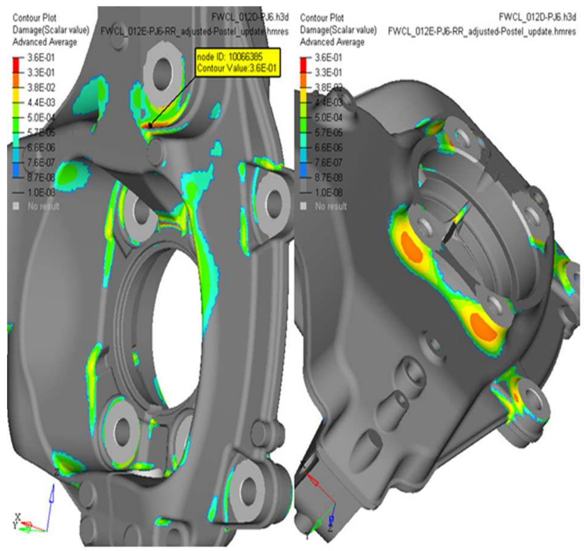

Fig. 27. Aluminium knuckle fatigue analysis results

Although the aluminum knuckle analysis result is slightly below the acceptance criteria, it can be considered as having passed the analysis since it is very close to the relevant value and will be physically verified by component level rig tests, and also because the acceptance criteria already include a safety factor.

5. ACKNOWLEDGEMENTS

This research work has been constituted from the study that “ Investigation of cast iron knuckle castability with aluminium alloy low pressure die casting and analyzes”, Master’s Thesis, Yildiz Technical University, Institue of Science, İstanbul, 2021 [6]

6. CONCLUSION

The biggest advantage of the transition to aluminium can be shown as the increase in the load carrying capacity of the vehicle which is very important especially for the commercial vehicles. This situation leads to a significant increase in customer satisfaction.

In addition, as knuckle being a significant contributor to vehicles unsprung mass, by decreasing the knuckle weight driving dynamics of the vehicle such as handling, cornering comfort and ride will be improved.

In the study, while the cast iron knuckle is 6.05kg, the aluminium design is around 4.53kg. Weight reduction is approximately 1.52kg per piece. Due to the use of two in the vehicle, the total weight reduction at the vehicle level is 3.04kg.

At the same time, for electric vehicles, which have become much more important today, the range of the vehicle increases with the decrease in the total weight. According to rough calculations, a decrease of 3kg in total weight of vehicle increases the total range of an electric vehicle with a range of 500km by 0.3km in the automotive industry, where the competition is very high.

Since the steering knuckle is a safety part, certain design rules have been followed while having design. It must be proven that the knuckle has a design that will eliminate all failure modes in the DFMEA document which the related severity is (9-10) out of 10.

Part unit costs can be mentioned as a disadvantage of the transition to aluminum. This transition could have a financial negative impact, as aluminum is more expensive than iron. In rough calculations, it can be said aluminum knuckle will be around 15% more costly.

After having an optimum design, it is time to check whether the designs made are suitable for the production method desired to be produced. In this study, filling and solidification analyzes were performed for both designs with the help of Magmasoft 5.4 casting simulations, respectively. With these analyzes, serious problems arising from the design and process are determined before the prototype and serial production, and design changes are made if necessary, before proceeding to the prototype tooling phase.

After having 2 designs suitable for both cast iron sand casting and aluminum low pressure casting methods, to investigate the interchangeability of these designs, the structural analyzes were completed before the proto tool phase, and how both designs would perform under the relevant vehicle loads were also examined. Both static strength and stiffness and dynamically fatigue analyses were performed. The relevant analysis loads are obtained by reducing the forces and moments collected from the wheel center from the vehicle level to the component level with test vehicles from special tracks that contain different road conditions. In the analysis results using these loads, it was observed that both cast iron and aluminium knuckles remained above the acceptance criteria in strength and fatigue analysis. [6]

Today, even though the convergence of finite element analyses and process simulations to reality has improved considerably with new developments, a 100% correlation between the real life and analyses have not been achieved yet. In conclusion although the aluminium knuckle is not as durable as the cast iron knuckle due to its material, it can be used for mid commercial vehicles as a result of the preliminary studies, but it must be physically verified with component, system and vehicle level tests before serial production since the tooling and design development costs are considerably high. [6]

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REALIZAREA ARTICULAȚIEI DE DIRECȚIE DIN ALIAJ DE ALUMINIU PRIN TURNARE LA PRESIUNE JOSĂ ÎN MATRIȚĂ ÎN LOC FONTĂ TURNATĂ ÎN FORME DE NISIP

Rezumat: În această lucrare, manufacturabilitatea și utilizabilitatea articulației de direcție care se află la sistemul de suspensie față al vehiculelor comerciale medii a fost investigată dacă ar putea fi substituită din aliaj de aluminiu prin metoda de turnare sub presiune joasă în matriță în loc de fontă cu turnare în forme de nisip cum se realizează în mod convențional. În studiul de referință detaliat, s-a observat că articulațiile utilizate în vehiculele comerciale sunt în general fabricate din fontă. Deoarece piese mai ușoare pot fi obținute prin realizarea articulației din aluminiu, am avut ca scop creșterea capacității de încărcare și, de asemenea, obținerea un consum mai bun de combustibil. În plus, acest model este, de asemenea, destinat să aibă o dinamică de conducere mai bună prin reducerea masei fără arc a sistemului de tracțiune și creșterea autonomiei pentru vehiculele electrice. În primul rând, ambele articulații, din fontă și aluminiu, au fost proiectate prin respectarea regulilor de proiectare aferente. Ulterior, au fost efectuate simulări de umplere și solidificare a turnării pentru a verifica metodele de turnare relevante. În concluzie, analizele de rezistență și oboseală au fost efectuate cu ajutorul unor metode cu elemente finite pentru a verifica adecvarea structurală a proiectelor, care au fost realizate sub sarcini similare ale vehiculului înainte de faza de prototipizare a sculelor.

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