Cost reduction of the motor beam design

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Abstract. Economic and practical reasons are increasingly forcing designers to work on solutions that shorten installation time, reduce vehicle weight, eliminate some of the errors that arise as a result of the production process, and those that can be successfully used on more than one project. An example of such a direction of development in terms of minimizing costs, reducing the risk associated with mechanical damage and obtaining high technological repeatability can be a motor beam used in high-speed trains belonging to the Pendolino family. The article concerns the cost reduction of the motor beam design. At the beginning a previous design made as a casting will be presented and finally the new concept of the beam made as forging will be proposed. In addition, both constructional forms will be compared in terms of strength, technology and economy.

1. Introduction

In the design of train car body shells, weight reduction becomes more and more important while maintaining appropriate mechanical strength, reduction of manufacturing time and technological repeatability. All these factors affect the reduction of the rolling stock production costs, its efficiency and quality of workmanship, as well as facilitation maintenance. These trends manifest themselves, for example, in the increasingly frequent departure from car body shells made of welded steel and replacing them with structures made as welded / riveted constructions from extruded aluminum profiles or on the development of design platforms on the basis of which many projects are carried out. It is no different in the case of various types of frames, brackets and beams that are mounted on the roof or underframe of modern trains.

Economic and practical reasons are increasingly forcing designers to work on solutions that shorten installation time, reduce vehicle weight, eliminate some of the errors that arise as a result of the production process, and those that can be successfully used on more than one project. Great emphasis is also placed on maintaining and, most preferably, improving the mechanical properties of the designed components as a result of the introduced changes.

Therefore constructional solutions made in casting, forging or the previously mentioned extrusion technology are gaining importance. It is worth noting that these technologies limit or eliminate the necessity of welding, which is particularly sensitive to fatigue and crack propagation in the case of aluminum.

An example of such a direction of development in terms of minimizing costs, reducing the risk associated with mechanical damage and obtaining high technological repeatability can be a motor
beam used in high-speed trains belonging to the Pendolino family, which will be the subject of this article. This beam is the fundamental component included in the engine mounting system.

In various scientific or commercial publications, we can find information on the differences between the casting and forging process for various components. For example, in the publication of the manufacturer of aluminum car rims [1], the advantages and disadvantages of the process of casting and forging of the rims have been presented, while the article [2] focuses on the fundamental differences between these two technological processes and the methods for selecting the best technological process for individual components.

Both documents [1], [2] do not indicate directly that any of the technological processes discussed (forging, casting) is better. The focus was to present the advantages and disadvantages of both processes and their characteristics. Most components that can be made in forging technology can also be made in casting technology and vice versa. The choice of the technological process depends on the geometric form of the component, the production volume and the strength requirements specified for the product.

The selection the of production method of the mechanical component depends also on machinery available, design specifications or requirements, cost of production, and type of material from which the mechanical component is to be made. For example, the automotive wheels are produced using casting or forging or their combination [3], [4]. However, many studies show that casting or forging process cannot meet the application requirements of complex shaped parts with high mechanical properties [5][6]. Many papers has been carried out on the casting and forging process of the automobile parts, while the publications dealing with the special train part – motor beam are not found by the authors. Motor beams differs from components described in the cited papers mainly with the size and application.

The aim of the article is to present and compare the advantages and disadvantages between the previous design of the motor beam made in the form of a cast and the current forging construction as well as an indication of the advantage of a forged design based on the premises concerning manufacturing, economic and strength technologies that ultimately influenced the decision to introduce mass production of the forging instead of the casting. For the current beam design there are also present the details about the calculation model, the values of allowable stresses and information on the considered load cases.

2. Description of operation and basic components included in the engine mounting system

In the MU (multiple unit) trains belonging to the Pendolino family, the engine is not directly located on the bogie but is placed below the underframe and connected to the reduction drive by means of the Cardan shaft. The seven-car train contains 16 motor beams, four on each of the four motor cars.

The engine mounting system consists of: two motor beams, two longitudinal cantilever beams, two fork-shaped crossbars and four springs.

![Figure 1. The location of the engine on Pendolino class trains a) and simplified diagram of the engine mounting system b).](image-url)
The motor is connected directly to couple crossbars in the shape of a fork through a bolted connection. These traverses, in turn, are connected to the cantilever beams by means of springs mounted on rubber elements. By contrast, the cantilever beams are bolted to the motor beams, and these are directly connected to the underframe. The location of the engine and simplified diagram of the engine mounting system is shown in the Figure 1.

3. Previous design of the motor beam
The previous version of the motor beam was made as a one-piece casting, empty inside. The design of the beam is shown in the Figure 2.

The beam was entirely made of EN AC-42200-T6 aluminum alloy. The casting process of such a beam was carried out in the sand casting method and it was very complex.

This form of the motor beam has as many advantages as disadvantages. The most important benefit of making the motor beam in casting technology was low weight. One beam weighed only 42 kg. This was due to the use of casting technology, which allows for a very free shaping of the structure, and to obtain a hollow shape. Thanks to the use of this technology, it was possible to make a beam in the form of a "box", which significantly reduced mass while maintaining appropriate strength properties.

The low weight of the beam, in addition to a positive impact on the energy efficiency of the vehicle, significantly facilitated assembly process below the underframe by employees (no need to use lifts, easier way of handling the beam during assembly).

Another advantage of this technology was the possibility of making a beam in a one-piece form. It allowed to reduce assembly time by not having to use connections (eg welded, screwed) and later verification during tests. The one-piece construction also had its disadvantage, which was described later in this chapter.

However, this beam concept also caused some inconvenience - first of all, the inconveniences concerning the maintenance of dimensional tolerance on such a large casted component as well as a uniform structure of the cast material, avoiding casting defects that could significantly reduce the strength of the beam.

The tolerance between the two extreme legs of the beam, spaced at 2400 mm, had to be kept within ± 2 mm. The tolerances of the beam shape were also small, requiring the adjustment of the outer contour of the beam to the gauge of the train and to the existing covers of the underframe. This was associated with the optimization of the casting process and its strict control.

Another inconvenience was the necessity to carry out a series of tests (X-ray examination and decolorization test) to detect casting defects.

Both inconveniences mentioned above were related to the fact that the casting beam, with the required tolerances of shape and dimensions, was able to be produced by only one company in the world. Therefore, the price of one beam was relatively high. This situation also posed a risk of not meeting the delivery deadline, which would mean delays in the delivery of trains.
The disadvantages of the solution made in casting technology include also the susceptibility of beams to the occurrence of mechanical damage during exploitation. This was due to the hollow beam form and the relatively small thickness of the aluminum layer in the driving direction of the train (5 mm). The beam was susceptible to damage caused by the impact of stones torn out from the railway embankment by aerodynamic whirls caused by a moving train or the impact of ice blocks.

What's more, the whole beam cast as one coherent part had to be replaced if it suffered damage by hitting a rock / blocks of ice, or it was damaged in an accident.

In relation to the above-mentioned drawbacks of the original structure of the beam made in casting technology, it was decided to redesign the beam and make it in the forging technology.

4. Current design of the motor beam
The current version of the motor beam has been made as 6 forgings connected together by means of screw connections. The design of the beam is shown in the Figure 3.

The beam is now entirely made of EN AW-6110 aluminum alloy.

In comparison with the beam made in the casting method, the forged beam is almost twice as heavy. Its mass is currently 71 kg (forged elements + fasteners + grounding tapes). The increase in mass results from the inability to make the beam in the form of a hollow structure, as was made in the case of casting. The beam should have a thicker aluminum face, in order to meet the strength requirements, (7 mm instead of the previous 5 mm) and should be more ribbed. The forging technology also forced the need to thicken the outer flange of the beam, because there was a apprehension that the material would be destroyed during the forging process. An increase in the weight of the beam by about 30 kg did not caused major disadvantages. Of course, the energy efficiency of the train has decreased, but the weight increase by 120 kg (4 beams 30 kg heavier on the motor car) is negligibly small (0.24% increase in weight in relation to the car) compared to the weight of the car. Relatively the forged beam has a very good coefficient of its mass to the mass of the supported equipment. It should be recalled here that two beams with a total weight of 142 kg hold the engine with the equipment with a total weight of 2090 kg.

Thickening and ribbing of the front aluminum layer (oriented normally to the drive direction of the train) positively influenced the strength properties of the entire beam. Now the beam is much less exposed to mechanical damage during exploitation, caused by the impact of stones torn from the railway embankment by aerodynamic whirls caused by a moving train or the impact of ice blocks.

Another advantage of a forged beam over a cast solution is the possibility of replacing damaged parts (e.g. during an accident) independently.

The advantages also include easier maintaining of the required dimensions and dimensional tolerance. This is due to the fact that the beam is produced in the form of smaller forgings connected to each other (on which it is easier to obtain a tighter tolerance than on a large cast component), and also due to hole tolerances that allow to eliminate dimensional errors during the forging process.

In the case of forging technology, it is not necessary to verify the beam with X-rays, because the forging process precludes the formation of shrinkage cavities that may have appeared during casting.
However, the biggest advantage of a forged beam over casted, is its price and the possibility of being made by more than one manufacturer in the world. The price of a forged beam compared to a casted solution is 33% lower, which with the need to use 16 beams per trainset and 448 beams per project gives very large savings.

Forged design of motor beam is not free from flaws. Above all, the disadvantage of this solution is the aforementioned higher mass than the casting solution, which mainly affects the difficulties related to the assembly of the beam below the underframe by employees (an adverse effect on the energy efficiency of the train has been described earlier and is negligible). Due to the increase of weight, it is now necessary to use lifters, which extends the assembly time.

As another inconvenience, the use of a large number of screws (24 M12 10.9 bolts per beam) can be mentioned, which extends the assembly process and also forces precise torque wrenches to be used and therefore requires trained personnel. The number of earthing tapes used has also increased, due to the necessity of earthing all 6 parts of the forged beam.

Nevertheless, the solution of the motor beam in the form of bolted together six smaller forgings has more advantages than disadvantages, and above all the price and flexibility in the selection of suppliers significantly exceeds the previous concept of a beam in the form of a one-piece cast.

5. FEM analysis of casting and forging beam

5.1. FEM model used for strength calculations
The FEM model used in the analysis is mainly a shell model (only fork-shaped cross-bars have been modeled using solid elements). All technological elements that do not influence the results (such as chamfers, fillets, etc.) have been removed from the FEM model.

The calculation model consists of 4 main parts: part of the underframe structure, two motor beams, two longitudinal cantilever beams and two fork-shaped crossbars.

The engine weight including equipment (1788 kg), cardan shaft (53 kg) and torque limiting clutch (40 kg) have been modeled as a concentrated masses, connected to appropriate interfaces.

The FEM model is shown in the Figure 4.

![Figure 4. FEM model – general view.](image)

The motor beam was modeled using quad4 shell elements (contribution of tria3 elements is below 1%). The motor beam calculation model is a non-linear model with modeled frictional contacts and bolt pretension between the parts included in the bolted connections. The choice of surface elements resulted from the necessity to reduce computational time while obtaining accurate results. In order to accurately express the presence in the beam model of inclinations resulting from forging technology, the surfaces that were characterized by the largest thickness increases were divided into narrow strips.
with a length of 5mm. The appropriate thickness is assigned to the each strip. In this way, the stiffness of the beam was realistically modeled.

Calculation model has been constrained on the both ends of the cut part of the underframe structure with all DoFs constrained.

Within the strength verification of the motor beam, the cases of static resistance for maximum loads and fatigue loads defined in the EN 12663-1 standard [7] as well as those resulting from engine operation were considered.

5.2. Results of analysis
The results of the analyzes show that the stresses in all considered load cases do not exceed the limit values.

Comparison of stress distribution on both beams is well demonstrable in cases where significant external forces are acting. These include cases of loading the beam with maximum longitudinal acceleration and maximum torque. Figure 5 presents stress maps for the casted beam and forged beam load with maximum longitudinal acceleration. Stress maps have been calibrated to the same values corresponding to each color. As can be seen, the distribution of stresses on both versions of the beam is similar. The most loaded are the outer legs, a little less internal, while in the middle part of the beams the stresses are close to zero.

![Figure 5. Comparison of the stress distribution (v. Mises) between the casted beam (a) and forged (b) [MPa].](image)

6. Conclusions
This article presents a comparison of the design of a motor beam made in the form of a casting and forging. For both constructions, economic, technological and strength aspects were compared. Forged beams are cheaper to produce and the manufacturing process itself can be implemented by a wide range of possible suppliers. It is crucial from the point of view of the company - it allows to obtain significant financial savings and to compare the offers and quality of production of various suppliers.

In terms of technology, the forged form provides greater resistance to inaccuracies in the technological process, which results from the assembly of several components by means of screw connections (tolerances can be eliminated during the assembly process of particular parts). On the contrary, in the case of a cast form, which is one monolithic body, on the one hand not requiring assembling as in the case of a forged form, and on the other hand, requiring high dimensional quality, which significantly affects the price of the casting. The forged product also has greater strength on stones or pieces of ice impact.

Taking into account the results of the strength analysis, it can be noticed that the state of stress in both versions of the motor beam (cast and forged) is very similar and only differs in maximum values. This proves the compatibility of both analyzes for both versions of the motor beam, because with the unchanged attachment points to the train chassis, the stresses are similar for both beam forms.
Considering the above conclusions, which prove the advantage of the forged design motor beam over the casted in many aspects, both economic, technological and endurance, it was possible to introduce the forging in the new ALSTOM design.

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