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Review of the Cost-Situation of a Lightweight Electric Vehicle Gearbox Housing through Topology Optimization and Additive Manufacturing

Steffen Jäger[1], Tilmann Linde

[1] *Furtwangen University*
Institute of Product and Service Engineering
Robert-Gerwig-Platz 1, 78120 Furtwangen
GERMANY
steffen.jaeger@hs-furtwangen.de
phone +49 7723 920 2424
cell +49 177 269 9166

Executive Summary

This study analyses the lightweight design and cost efficiency of a gearbox housing for electric vehicles (EVs) by combining topology optimization and additive manufacturing (AM). A 21% weight reduction was achieved through an X-shaped structure without compromising torsional stiffness. To examine cost-effective production, a hybrid manufacturing approach combining Laser Metal Deposition (LMD) and turning was developed and evaluated. A material study confirmed that aluminium alloys provide the best balance between weight and stiffness among the tested materials. However, despite the manufacturing feasibility, the economic analysis showed that hybrid manufacturing does not offer cost advantages compared to full additive manufacturing or conventional casting. These findings highlight the potential and current limitations of AM technologies for lightweight EV drivetrain components.

Keywords: Electric Vehicles, Vehicle manufacturing, Materials for EVs, Modelling & Simulation, Drive and Propulsion Systems

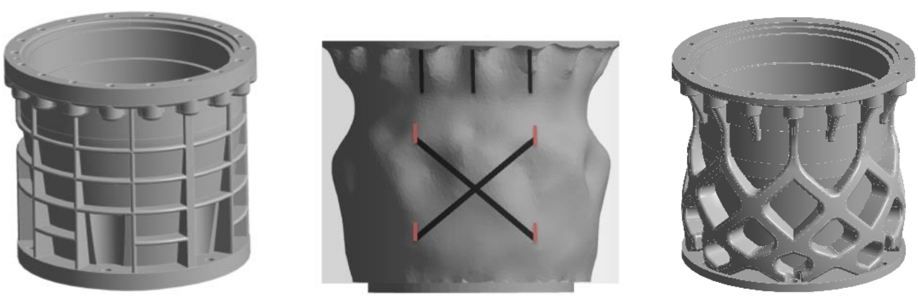
1 Introduction

Increasing electric vehicles' powertrain efficiency represents a key area of focus within the automotive industry. Utilising gearboxes facilitates the use of lighter electric motors that operate at higher maximum rotational speeds, leading to cost reductions. Achieving an extended range in vehicles is of significant importance, and this can be achieved through the implementation of lightweight designs in drivetrain components such as gearbox housings. Additive manufacturing (AM), particularly of aluminium alloys, enables the production of lightweight and flexible drivetrain components. Technologies such as Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) allow for the realization of complex geometries tailored to specific functional requirements. The development of novel manufacturing technologies has led to significant advancements in the efficiency and speed of aluminium part production,

thereby enhancing the competitiveness of this technology [1]. Additive manufacturing by laser melting of aluminium alloys is also employed in other branches of industry, where it can be used to manufacture gearbox housings [2]. Another widespread additive manufacturing process is Laser Metal Deposition (LMD), which is increasingly being used in a variety of industrial sectors [3]. This is an additive manufacturing technology that offers significant design flexibility, enabling the creation of complex geometries [4]. In particular, LMD enables the manufacturing of complex designs that would be difficult or impossible to achieve using conventional methods [5]. Topology optimization can be implemented in the design of a component to achieve lightweight structures and to identify non-critical regions where material can be removed without compromising its structural behaviour [6, 7]. By combining AM with topology optimization, highly efficient lightweight designs become feasible that are specifically adapted to load paths and weight.
This study focuses on the optimization and manufacturing of a specific gearbox housing used in electric vehicle drivetrains. The noise level of electric vehicles with multi-speed gearboxes is a topic of ongoing research, driven by the goal of developing quieter and more comfortable vehicles. Optimizing gearbox housings has the potential to substantially reduce noise generation, thereby enhancing user perception and evaluation [8]. Furthermore, gearbox housings are also being analysed in the commercial vehicle sector with regard to reduced weight and noise emission [9]. Additive manufacturing, and more specifically 3D metal printing, has already become firmly established in a considerable proportion of the electromobility industry [10]. This technology facilitates the production of components that have been developed with specific consideration for the requirements of electromobility. With regard to additive manufacturing, the most significant cost parameters are processing cost, followed by material cost. In the case of parts with highly complex geometries, AM can be more suitable and cost-effective [11]. Further research and development are required to fully realise the benefits of AM, including functional integration and increased power density, and to expand its application areas. However, challenges related to cost calculation and process chain optimization still need to be addressed.
In addition, new approaches such as hybrid material combinations (e.g., aluminium with magnesium or titanium) are evaluated to further enhance mechanical performance while minimizing weight. Numerical simulations, including structural and modal analyses, are employed to validate the design.
This study explores the combined use of topology optimization and additive manufacturing techniques to design a gearbox housing that meets the structural and lightweight demands of electric vehicle powertrains.

2 Lightweight Design

Building upon previous work by the authors [12], this study focuses on the application of topology optimization to a specific gearbox housing provided by an industrial project partner, cf. figure 1a. The objective is to achieve a significant weight reduction and preserving the housings' stiffness. It is part of a planetary gearbox, carries two ring gears and is exposed to both static and dynamic loads. Static loads act on the flanges where the housing is mounted. Additional torsional loads are incurred by the tooth mesh during gearbox operation. Consequently, the torsional stiffness is regarded as a relevant comparison parameter.



(a) (b) (c)

Figure 1: (a) Original gearbox housing, (b) Optimization region and optimization result, (c) Optimized housing.

An integral design approach was used to propose a monolithic lightweight gearbox housing. Based on the defined load cases (static mounting forces and dynamic forces from gear meshing), the specific optimization region, the optimization objectives and other boundary constraints (e.g. min. wall thickness) the topology optimization is performed. The optimization objective is to minimize the mass while maintaining torsional

stiffness within acceptable limits. Both the housings' given inner profile and the flanges (distance, diameter etc.) are part of the excluded region. They cannot be affected by the optimization algorithm. The optimization region is shown in figure 1b (light grey region). Topology optimizations' result shows an x-shaped structure as marked in figure 1b. The ring gear mounting points are located directly at the tips of the x-structure. Thus, the load will be passed directly on to the supporting structure. This structure' shape and location strongly affects the housing' torsional stiffness. That allows reducing the housing' wall thickness. Furthermore, stiffening ribs are indicated at the bolting points on the upper flange.
For the selected optimized design (cf. figure 1c) the weight has been reduced by approx. 21 % compared to the original housing, while torsional deformation increased by only about 5 %, remaining within acceptable design limits. This geometry is the basis for both the additive manufacturing concept and the hybrid material study below.

3 Additive Manufacturing Concept

To fabricate the optimized structure, AM was chosen for its ability to produce complex geometries. In the case of the optimized gearbox housing, additive manufacturing is feasible but requires careful evaluation regarding size, mass, and economic viability. The manufacturing concept as shown in figure 2 was developed. It is based on Laser Metal Deposition and includes a hybrid material design idea.
The inner part is intended to be a turned part and it serves as a support structure for the additive manufacturing process. Figure 2 shows a view of the housing with localized reinforcement in high-load areas achieved by this hybrid material approach. The turned part' geometry is given by the dimensions of the bearings, the ring gears and sealings.

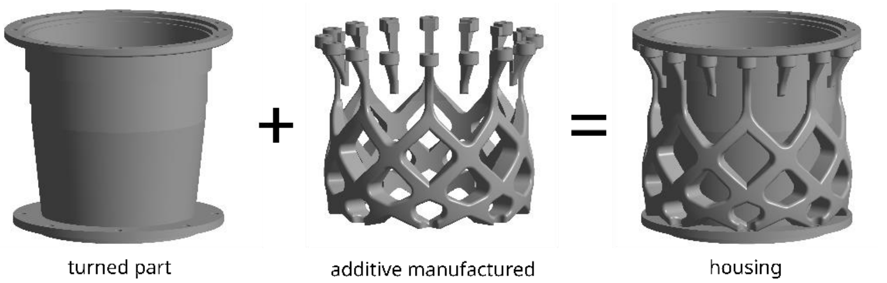


Figure 2: Manufacturing concept combining turned part and additive manufactured structure.

The turned part' outer profile follows both the inner profile and the intention of non-complex manufacturing. To decrease additive manufacturing time and material consumption, the mounting flanges are added to the turning part. While this is more challenging for additive manufacturing, it should bring benefits in terms of cost. Printed flanges are technically feasible, but significantly increase the time required for printing due to their volume. The outer profile (see figure 2, additive manufactured) will be made using Laser Metal Deposition. As this allows adding complex structures directly on 3D-Surfaces, the stiffening structure as described above can be produced without further processing steps.

4 Material Study

The primary material selected was aluminium, due to its compatibility with LMD processes and favourable specific mechanical properties. However, a hybrid approach integrating magnesium and titanium in high-stress areas was also evaluated to enhance mechanical strength without significantly increasing weight. Finite element analysis (FEA) and modal analysis were used to evaluate the structural and dynamic behaviour of the optimized gearbox housing under various operational loads. The simulation setup follows the methodology established in [12]. These simulations analysed deformation, stress distribution, and natural frequencies to ensuring that the design met torsional stiffness requirements and minimized potential resonance issues. The proposed simulation framework can be used to assess the natural frequency and the frequency response of the gearbox housing. Both are critical parameters for EV applications where noise and vibration are more noticeable due to the absence of an internal combustion engine (ICE). Results show a shift in natural frequencies compared to the original design, which can reduce the risk of resonance at typical operating speeds. This analysis is particularly relevant as EV components must be designed with stricter noise, vibration, and harshness (NVH) requirements to ensure driver comfort [13]. The following material study represents an extension of the outlined approach with a view to examining further aspects.

The utilisation of Laser Metal Deposition in conjunction with turning can result in substantial reductions in material consumption, machine time, and build rates. Laser manufacturing is very expensive compared to conventional processes such as turning and milling, which is why the focus here must be on significant reduction of costs. In addition to the above presented combination of different manufacturing processes, the use of various materials will also be examined. This is to determine whether, in addition to the advantages of the manufacturing combination, benefits in the mechanical behaviour of the structure can be achieved.
Testing the behaviour of the housing with different materials, an aluminium alloy, a titanium alloy, a magnesium alloy and a stainless steel were selected to cover a wide range of commonly used metals. Table 1 shows the details of the chosen materials. All selected materials are compatible with Laser Metal Deposition in principle. However, detailed manufacturing aspects such as processing parameters were not considered at this stage, as the focus lies on mechanical suitability.

Table 1: Properties of considered materials.

name	**material designation**	**density in** ***g/cm³***	**Youngs modulus in** ***MPa***	**Poisson's ratio**	**specific modulus in** ***MPa·cm³/g***
Aluminium	AlSi7Mg	2.68	70,000	0.350	26,119.4
Titanium	Ti6Al4V	4.43	110,000	0.340	24,830.7
Magnesium	MgAl3Zn1	1.775	44,650	0.305	25,154.9
Stainless Steel	X5CrNiMo17-12-2	7.954	195,000	0.250	24,516.0

As described in the topology optimization section, all the optimized housings will be compared to the original housing and its specific mechanical behaviour. In the present material study, the stiffness of the housing is also compared and evaluated based on its rotational stiffness. This is determined by fixing the housing on one side, applying the known mechanical loads from the gear mesh, and measuring the deformation (rotational) at the opposite end. Additionally, in this study, a modal analysis will be performed under the same boundary conditions to gain insights into whether the choice of materials has an impact on the natural frequencies of the housing. Knowledge of the natural frequencies is important if the dynamic and acoustic behaviour of the gearbox is to be evaluated in the further development steps. The authors presented a method for this in a previous article [13, 14].

Table 2: Material study' results.

no.	**version**	**turned part material**	**stiffening structure material**	**weight in** ***kg***	**rotational deformation in** ***µm***	**natural frequency, first mode in** ***Hz***
1	2	Aluminium	Magnesium	6.40	11.70	1383
2	1	Aluminium	Magnesium	6.44	11.33	1376
3	2	Titanium	Magnesium	8.12	9.21	1392
4	1	Aluminium	Aluminium	8.41	9.34	1382
5	1	Titanium	Magnesium	9.93	8.47	1334
6	2	Titanium	Aluminium	10.04	7.48	1390
7	1	Aluminium	Titanium	10.76	7.51	1337
8	1	Titanium	Aluminium	11.21	7.22	1359
9	2	Stainless Steel	Magnesium	11.59	6.47	1362
10	2	Stainless Steel	Aluminium	13.51	5.33	1408
11	1	Stainless Steel	Magnesium	15.83	5.32	1294
12	1	Stainless Steel	Aluminium	17.11	4.76	1330

Table 2 shows the results of the material study. It is to be read as follows. The *turned part material* and *stiffening structure material* columns show the material assigned to each part of the housing for the simulation. Details of the materials are given in table 1. The result parameters include weight, rotational deformation and first natural frequency. The *version* column indicates that there are two different versions for the same material combination. First results have shown that moving the flanges (the upper or lower end of the turned part, cf. figure 2) from the turned part into the LMD part could offer advantages. Version 1 corresponds to the geometry shown in figure 2, while version 2 has the flanges manufactured additively. Depending on the density of the material, this could increase the cost of additive manufacturing, but it could also significantly reduce the weight.

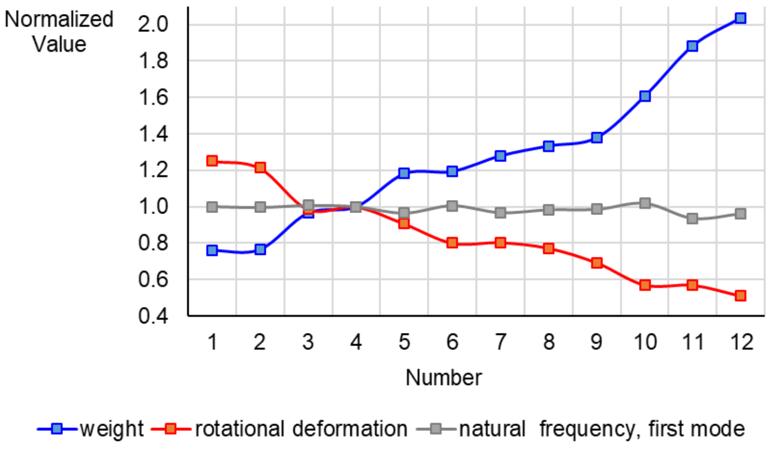


Figure 3: Material study' results.

The data from table 2 were plotted in figure 3, normalized using the Aluminium-Aluminium combination as the baseline (see no. 4 in table 2). As weight increases from version 1 to 12, rotational deformation generally decreases. This behaviour follows the general trend that Young's modulus increases with density among the considered materials, see table 1. Due to the used materials, there was no significant improvement in stiffness when taking the increased weight into account. Considering the specific modulus, as shown in table 1, the ratio of Young's modulus to density of the aluminium alloy is the best among the considered materials. This indicates that the aluminium alloy is the best choice for achieving high stiffness with low weight, regardless of the geometry, as confirmed by the simulation results.

Comparing part numbers 6 and 7, a notable observation can be made. As both have the same material combination but come from different geometry variants, the flanges remain the same material (aluminium in this case). Both the resulting rotational deformation and the weight remain at the same level. This indicates that both the turned part and the stiffening structure have a similar influence on the rotational stiffness. All results for the first mode of natural frequencies remain almost constant. Therefore, the choice of material appears to have a negligible effect on the natural frequencies. This could also be explained by the specific modulus given in table 1.

From a manufacturing aspect, the use of aluminium alloys for both the turned part and the stiffening structure is the most practical option. This is because, even when different versions of aluminium alloys are used, they have a similar melting temperature, which makes it easier to adjust the Laser Metal Deposition process. In addition, properties such as corrosion resistance, temperature resistance and biocompatibility, which are offered by titanium alloys, are not relevant for the given application in a gearbox housing. Aluminium therefore fulfils all the requirements. In addition, the material price of aluminium is generally lower than that of magnesium or titanium [15].

In the variants where the turned part is made of stainless steel (no. 9-12), the use of a steel results in significantly less rotational deformation compared to the other materials. This results in new design freedom, for example with regard to the wall thickness of the turned part, in order to reduce the weight and at the same time achieve a similar rotational deformation. This approach to adapting the design was not pursued in the present study.

5 Cost Evaluation

In this section, three different manufacturing approaches for the optimized gearbox housing are evaluated: hybrid manufacturing using Laser Metal Deposition (LMD), full additive manufacturing using Selective Laser Melting (SLM), and conventional aluminium casting. LMD is intended for the application of the external profile structure to the turned part. The costs shown for this only include the application of the structure, without the costs for the turned part. Both fixed and variable costs are taken into account for the manufacturing process. The total cost of Laser Metal Deposition is compared to the cost of manufacturing methods that do not consider hybrid design.

The costs associated with an additively manufactured component are comprised of the following: pre-processing cost, material cost, processing cost, and post-processing cost. Figure 4 illustrates a comparison of the normalized costs of the aluminium housing fabricated via SLM. The shown price represents the most cost-effective of several quotes from manufacturing service providers. The authors' observation of the market reveals a substantial decline in price. It has decreased by approximately 28 % compared to the price two years ago. This development can be attributed to a combination of factors. Possible causes include technological advancements in additive manufacturing, increased market competition, and fluctuations in raw material prices (metal powder). Furthermore, learning effects and investments in research and development of new machines and processes may have also contributed to an optimization of production costs, thereby leading to a reduction in price.

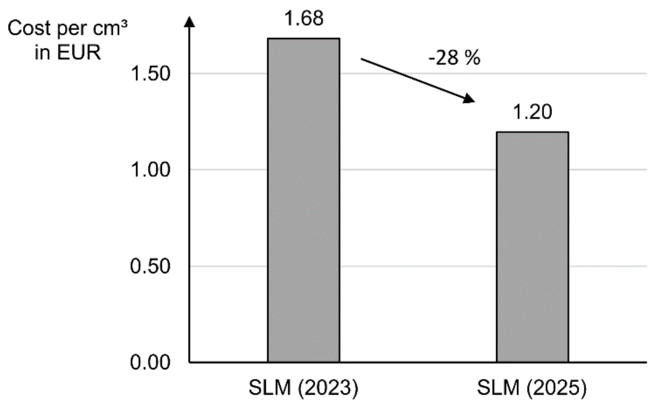


Figure 4: Difference in normalised costs for Selective Laser Melting at service provider manufacturers.

Quotes were obtained from contract manufacturing service providers for additive manufacturing using SLM. Moreover, the cost of aluminium casting is incorporated into the analysis. As the number of units produced is low (up to 100), aluminium die-casting is not included in this evaluation. The financial outlay required for Laser Metal Deposition and aluminium casting was derived from an industry project partner.

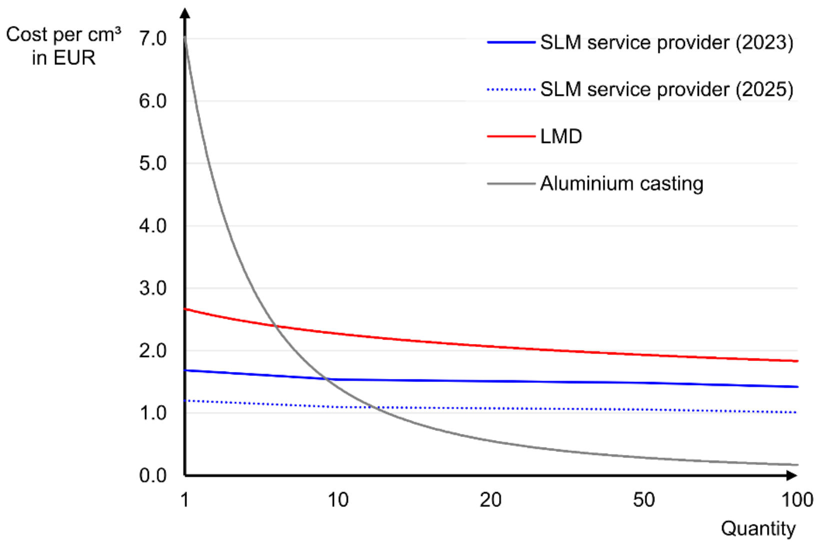


Figure 5: Manufacturing cost comparison for different manufacturing methods.

Figure 5 shows the cost per volume unit against the quantity of units. This figure presents a comparison of production costs between traditional manufacturing methods and those utilising additive manufacturing methods. The traditional casting method is characterized by high fixed costs, which, however, exhibit a pronounced decrease with increasing production quantities due to the relatively low variable costs. Consequently, a cost per unit volume of approximately 0.20 €/cm³ can be achieved at a production quantity of 100 units. In contrast, the hybrid manufacturing method emerges as the most expensive variant, as the variable costs exhibit a relatively modest decline with increasing production quantities. A similar trend is observed for the contract manufacturer's quote for Selective Laser Melting printing. Nevertheless, some providers are able to offer more substantial discounts for larger production quantities due to more efficient utilization of assembly space. This enables the attainment of a cost per unit volume of less than 0.50 €/cm³ for SLM-manufactured aluminium components at a production quantity of 100 units.

6 Conclusion

This study demonstrates that topology optimization combined with additive manufacturing enables significant weight reduction of gearbox housings for electric vehicle applications while maintaining required mechanical properties. A hybrid manufacturing concept, integrating turning and LMD, was developed to facilitate the production of complex, optimized geometries. Although the feasibility of this approach was confirmed, the economic evaluation revealed that it does not offer a cost advantage over full additive manufacturing or conventional casting under current conditions.

The material study showed that aluminium alloys remain the preferred choice due to their superior specific modulus and favourable manufacturing characteristics. Alternative material combinations provided no significant benefits in terms of torsional stiffness or dynamic behaviour. However, the use of steel for the turned part demonstrated a considerable increase in stiffness, opening up new design possibilities such as reducing wall thickness to achieve a lighter design without sacrificing mechanical performance. Although this approach was not pursued in the present study, it offers promising potential for future projects.

Future work will focus on optimising hybrid manufacturing strategies to improve cost efficiency and exploring material and design adaptations further to meet specific load and NVH requirements. Additionally, topology optimisation and additive manufacturing offer promising potential for further weight and efficiency improvements in EV powertrains when applied to other drivetrain components.

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Presenter Biography

Steffen Jäger has been a professor at the Furtwangen University‘s Institute of Product and Service Engineering since 2018. His teaching focus is on development and design methodology. After completing his doctorate in the Drive Systems Research Group at the Karlsruhe Institute of Technology (KIT), he worked in a spin-off he co-founded. The focus of his research activities is product development as well as the validation of drive systems and their components.