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SIMULATION OF HYBRID AND POROUS SPUR GEARS WITH FEA

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Abstract. Simulating hybrid and porous (HyPo) materials is challenging due to the wide variation in material properties. HyPo structures, typically consisting of a steel surface layer and a porous metal foam core, offer a balance of strength, durability, and reduced weight. Additive manufacturing enables flexible material combinations, with the Collaborative Research Center CRC/TRR 375 currently investigating steels (17-4 PH, 316L) and the aluminium alloy AlSi10Mg.
A key application is spur gears for highly loaded systems. To assess their performance, a finite element framework was developed by extending an existing model for fibre-reinforced plastic gears. The adaptation allows hybrid material combinations and property gradations to be incorporated. The framework can automatically generate gear geometries and apply modifications such as tooth root or tip relief.
Using this tool, a study on the influence of surface layer thickness was carried out. The results advance the understanding of HyPo materials in gear applications and provide a basis for refining ISO 6336 to enable analytical design methods for such gears.

1 INTRODUCTION

The design and manufacture of machine elements is still largely dominated by steel components. Non-metallic alternatives, particularly plastics, are confined to applications in which their advantages in weight reduction and cost efficiency justify their use. Within the Collaborative Research Center CRC/TRR 375 [2], research is now directed towards a novel material class: hybrid structures that combine a graded, foamed metallic core with an additively manufactured surface layer. These materials, referred to as “HyPo” (hybrid and porous), integrate the advantages of both structural concepts, offering mechanical strength at the surface while maintaining low weight and tailored properties in the core. Despite their promising characteristics, HyPo materials have received only limited attention in the scientific literature so far.
Traditionally, highly loaded components such as gears and bearings are manufactured from steel due to its favourable balance of hardness, fatigue resistance, and ductility [5]. Hybrid approaches,

however, enable functionally graded designs that combine different material behaviours within a single component. A particularly relevant field of application is the development of lightweight gears. Conventional lightweight designs include thin-rim concepts [6, 7], selective material removal from low-stress areas [14], or the direct use of additive manufacturing [12]. These strategies reduce mass and can significantly influence the dynamic behaviour of gears. For example, [7] demonstrated that optimised thin-rim geometries reduced dynamic meshing forces by up to 70%, thereby improving noise, vibration and harshness (NVH) performance. Further studies explored bimetallic gear concepts produced by forging, highlighting the effect of rim thickness on tooth root stresses [13].

In contrast, HyPo materials represent a fundamentally different approach compared to conventional metal foams. Established methods for producing cellular metals—such as melt foaming with gas or blowing agents, or spray-based techniques [4]—do not allow for a freely formed metallic surface layer or a graded foam structure. HyPo manufacturing, by combining additive processes with foamed precursors, enables both. Current developments within CRC/TRR 375 focus on welding-based wire arc additive manufacturing (WAAM) and powder-based laser directed energy deposition (L-DED), using foamable aluminium alloys (e.g. $\mathrm{AlSi10Mg}$) and steel foams (316L, 17-4PH) as core materials [2].

For gears in particular, the NVH performance represents a central motivation for the use of HyPo structures. By employing a core with reduced stiffness, an increased contact ratio under load and consequently reduced noise levels can be achieved [7]. To evaluate these effects, the present work investigates the stresses and strains of foamed cores combined with additively manufactured outer layers and analyses the implications for NVH characteristics.

To this end, a dedicated macroscopic simulation framework was developed within CRC/TRR 375. [3] This finite element (FE) environment allows automatic geometry generation of spur gears, material property assignment, and efficient adaptation to hybrid structures.

As in previous work, this study investigates the influence of surface layer thickness on tooth root stress, load-dependent contact ratio, and angular deviation of HyPo gears. In contrast to earlier analyses, however, the present investigation employs newly derived material data based on formulations from the literature, which differ from the datasets used previously.

2 METHOD

The study presented in this paper builds upon a finite element (FE) simulation framework introduced in earlier work [3]. Originally developed for the simulation of fiber-reinforced plastic spur gears, the framework was adapted to account for the specific material characteristics of HyPo spur gears. In its current form, it enables the generation of gears with locally varying material properties [9, 10]. The framework combines *Matlab* for geometry generation and post-processing with *Abaqus CAE*, which carries out the main FE simulations.

The FE model used in this study employs eight-node, linear, reduced-integration, hourglass-controlled elements (C3D8RT). This element type was chosen because it significantly reduces computation time compared to fully integrated elements. To further improve efficiency, only one half of the gear geometry is modeled. This is achieved by splitting the gear along the midplane and applying corresponding symmetry conditions. The complete tooth mesh is derived from partial meshing across three teeth. Gear movement is constrained such that both gears can only rotate around a central reference point.

In this study, both gears share identical dimensions, resulting in a gear ratio of $i = 1$. Consequently, the ideal input torque equals the ideal output torque. The material composition, however, differs: one gear is made of conventional steel, while the other is a HyPo gear featuring a porous foam core combined with a solid surface layer.

As described in [3], the framework was extended to incorporate the distinctive characteristics of HyPo gears, specifically their foam core and surface layer. Details on the simulation setup can be found there. The focus of this work is on tooth root fracture as the primary damage mechanism, since it directly limits the gear's ability to withstand bending forces. Other damage modes, such as pitting, can often be tolerated to some extent [11, 15].
Pitting is strongly influenced by surface HERTZIAN pressure, which is expected to be lower in HyPo gears due to their reduced YOUNG's modulus [8]. Therefore, the dominant failure mechanism of HyPo gears is expected to be tooth root breakage, which is the main subject of investigation in this study.

3 STUDY ON SURFACE LAYER THICKNESS

The simulations were performed with an output torque of $T_{\text{output}} = 10\,\text{Nm}$, selected on the basis of a preliminary study that examined the tooth root stresses in the HyPo gear. The input speed was set to $n = 1000\,\text{min}^{-1}$.
In the following, the material data and the gear geometry are described in detail.

3.1 Material data

The material data for the foam core of the HyPo gear was derived from an empirical correlation presented by ASHBY et al. [1]. This correlation relates the relative density $\rho_{\text{foam}}/\rho_{\text{solid}}$—defined as the density of the foam normalized by that of the solid base material—to various material parameters such as the YOUNG'S modulus, based on results for different industrial metal foams.
Since experimental material data within CRC/TRR 375 are not yet available, this approach was adopted to approximate the mechanical properties of the foam. The corresponding equations are given as follows:

$$E_{\text{foam}} \approx E_{\text{solid}} \cdot \left(\frac{\rho_{\text{foam}}}{\rho_{\text{solid}}}\right)^2 \tag{1}$$

$$G_{\text{foam}} \approx \frac{3}{8} \cdot G_{\text{solid}} \cdot \left(\frac{\rho_{\text{foam}}}{\rho_{\text{solid}}}\right)^2 \tag{2}$$

$$\nu \approx 0.3 \tag{3}$$

Based on a relative density of $\rho_{\text{foam}}/\rho_{\text{solid}} = 0.5$, the foam properties summarized in Table 1 were derived. For comparison, the material parameters of the surface layer and the reference steel gear are also listed. The YOUNG's Modulus and Shear Modulus of the foam core differ from those of the

Table 1: Material properties of the foam core and the surface layer

	Relative Density ρ/ρ_s / -	**Young's Modulus E / MPa**	**Shear Modulus G / MPa**	**Poisson's Ratio ν / -**
Surface Layer/ Steel Gear	1	210000	80800	0.3
Foam Core	0.5	17500	2437	0.3

steel surface layer by approximately one order of magnitude. These values represent approximations derived from the empirical correlation and will be validated in future work once experimental data from CRC/TRR 375 become available.

3.2 Geometry

The gear geometry was derived from the guideline VDI 2736 [15], which specifies several reference geometries. One of these served as the basis for the present study. The corresponding dimensions are listed in Table 2. In addition, following [16], a linear tooth tip relief of $c_\mathrm{a} = 50\,\mu\mathrm{m}$ and $c_\mathrm{l} = 100\,\mu\mathrm{m}$ was applied to both gears to reduce stress concentrations.

Table 2: Gearing data of the reference gears for spur gearboxes, adapted from [15]

Size	Symbol	Unit	Size 2
Center distance	a	mm	60
Number of teeth	$z_1; z_2$	-	30; 30
Normal module	m_n	mm	2
Pressure angle	α_n	$^\circ$	20
Helix angle	β	$^\circ$	0
Tooth width	$b_1; b_2$	mm	12; 12
Tooth tip rounding radius Gear 2	r_K2	mm	0.125
Profile shift factor	x_1 x_2	- -	0.2755 -0.2755
Reference profile factors (Gear 1; 2)	h^*_aP h^*_fP ρ^*_fP	- - -	0.95; 1.05 1.19; 1.10 0.2; 0.2

For the present study, the relative surface layer thickness, defined as $t_\mathrm{rel} = \frac{t_\mathrm{abs}}{m_\mathrm{n}}$ [3] and illustrated in Figure 1, was varied in the range $t_\mathrm{rel} = 0.05 \ldots 0.4$.

4 RESULTS

In these simulations, two main properties of the gear contact were evaluated. The first is the maximum tooth root stress σ_F, defined as the global maximum stress occurring in the root of a single tooth during meshing. This parameter represents the highest stress experienced by the teeth in the gear pair. If it exceeds the material's tensile strength, tooth root fracture may occur, potentially causing the tooth to break off. If the tooth root stress remains above a critical level under cyclic loading for a sufficiently long duration, fatigue failure may also occur, even if the material's tensile strength is not exceeded.

The second property is the load-dependent contact ratio, which quantifies the average number of teeth in contact at any given time. This ratio increases with tooth flexibility, which is particularly pronounced in gears manufactured from HyPo materials. A higher contact ratio is associated with reduced noise, vibration, and harshness (NVH), making it a desirable characteristic for the present study.

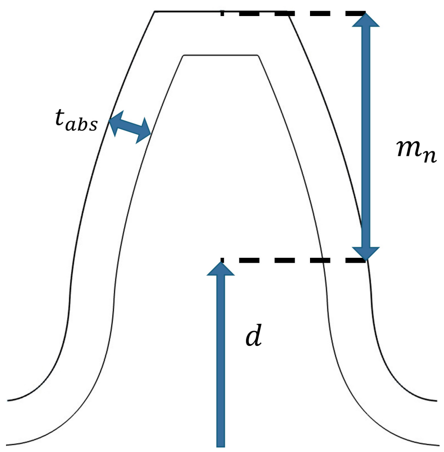

Figure 1: Absolute surface layer thickness t_{abs} and modulus m_{n} (measured from the pitch circle diameter d) of a HyPo gear

4.1 Maximum tooth root stress

The maximum tooth root stress σ_{F} for different relative surface layer thicknesses is shown in Figure 2, together with the corresponding values for gears made entirely of steel and aluminum. It should be noted that the applied torque of $T = 10\,\mathrm{Nm}$ is sufficiently low for steel and aluminum gears to exhibit nearly identical stress levels. A negative linear correlation can be observed, which is

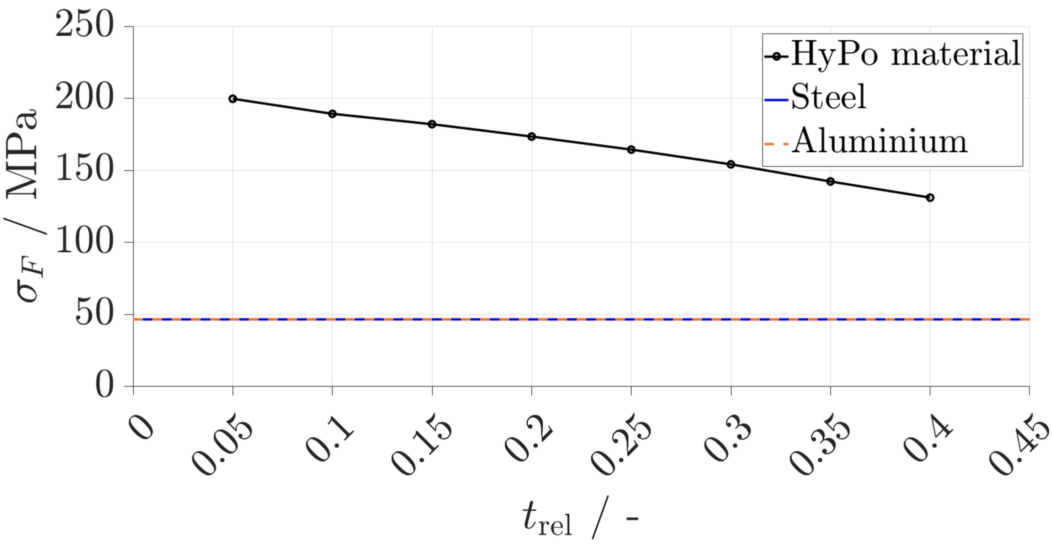

Figure 2: Maximum tooth root stress σ_{F} of HyPo gears with varying relative surface layer thicknesses t_{rel} (black) compared to solid aluminium (orange) and steel (blue) gears.

expected since the gear becomes stronger as the proportion of steel increases and the proportion of foam decreases. The theoretical maximum strength corresponds to a fully steel gear, represented by the blue line, while the dashed orange line indicates the value for a fully aluminum gear. The tooth root stress exhibited by the HyPo gear is approximately one order of magnitude higher than in both reference cases. Under static loading, these stresses remain below the tensile strength of the steel surface layer in which they occur. Under dynamic loading, however, a more detailed analysis would be required to predict potential fatigue and assess the service life of the gear.

4.2 Contact ratio under load

The load-dependent contact ratio represents the average number of teeth simultaneously in contact. While its minimum value is determined by the gear geometry, higher values can be achieved when the teeth exhibit increased flexibility. In general, a higher contact ratio leads to reduced noise levels in gear operation [7]. Figure 3 illustrates the contact ratio as a function of the relative surface layer thickness. As shown, a thinner steel layer results in a higher contact ratio and thus quieter gear behavior. Compared to gears manufactured entirely from steel or aluminum, HyPo gears achieve a noticeably higher contact ratio.

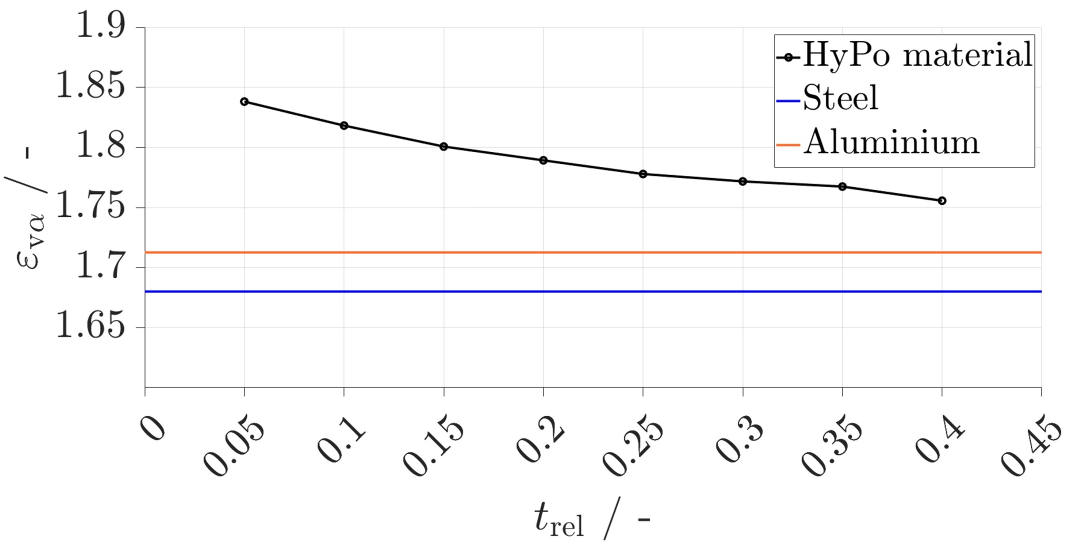

Figure 3: Contact ratio $\epsilon_{v\alpha}$ of HyPo gears with varying relative surface layer thicknesses t_{rel} (black) compared to solid aluminium (orange) and steel (blue) gears.

5 DISCUSSION

The results presented in section 4 show an expected relationship between the relative surface layer thickness and both the tooth root stress and the load-dependent contact ratio. The thicker the surface layer, the stronger the gear becomes due to the higher proportion of steel. This trend is consistent with the theoretical expectation that tooth root stress decreases as the contribution of the weaker foam core is reduced. In contrast, thinner surface layers increase gear flexibility, which in turn raises the contact ratio and thus improves acoustic behavior.

In comparison to the earlier work [3], which primarily focused on adapting the simulation framework and employed material parameters directly taken from the literature, the present study introduces a refined material modeling approach. Instead of relying on tabulated values, a theoretical foam with a relative density of 50% was derived using the same empirical relation that also underlies the data referenced in [3]. This ensures consistency with previous work while at the same time providing a more tailored representation of HyPo gears, thereby enabling a more application-oriented assessment.

These findings highlight the inherent trade-off between mechanical strength and NVH performance in HyPo gears. A higher proportion of steel increases load-carrying capacity but reduces the NVH bene-

fits, whereas thinner surface layers improve NVH characteristics at the expense of tooth root strength. Compared to conventional steel and aluminum gears, HyPo gears demonstrate a significantly higher contact ratio, confirming their potential to reduce noise and vibration in practical applications.
It should be noted, however, that the present study focuses solely on tooth root fracture as the dominant failure mechanism. Other forms of damage, such as pitting, wear or separation of the two layers, may also become relevant under real operating conditions and should therefore be considered in future investigations. Moreover, no experimental validation of the presented results has been carried out to date. Such validation is planned within the framework of CRC/TRR 375 and will provide an essential basis for assessing the accuracy of the simulations. The present analyses further assume idealized gear geometries and loading conditions, whereas manufacturing imperfections, material heterogeneity, and dynamic effects could significantly influence the observed behavior.
Overall, the results demonstrate that HyPo gears provide a promising balance between structural integrity and improved NVH characteristics. By tailoring the relative thickness of the steel surface layer, the mechanical and acoustic properties can be adjusted to meet specific application requirements.

6 CONCLUSION

This study investigated the influence of the relative surface layer thickness on the mechanical and acoustic behavior of HyPo gears using an adapted FE simulation framework. The results confirm that increasing the steel surface layer enhances tooth root strength, while thinner layers improve the load-dependent contact ratio and thus NVH performance. Compared to conventional steel and aluminum gears, HyPo gears demonstrate a significantly higher contact ratio, highlighting their potential for noise and vibration reduction. Overall, the findings show that HyPo gears offer a tunable balance between structural integrity and acoustic benefits, which can be tailored to application-specific requirements by adjusting the steel-to-foam ratio.
Future work will focus on the development of a dedicated design methodology for HyPo gears based on the ISO 6336 standard. This will provide a systematic framework for dimensioning and verifying HyPo gear designs, thereby enabling their practical application in engineering practice.

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