Design and production of innovative transmission components with additive manufacturing

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Abstract

The Automotive market is showing a growing necessity to vehicles efficiency improvement and emissions reduction. This goal requires a holistic design approach able to integrate each optimization dimension of the vehicle design. Weight reduction, more efficient IC engines and transmissions (powertrains), noise reduction and functional integration are all critical projects deliverables. Recent and future challenges demand today more than in the past a reconsideration and transformation of the design and production processes able to explore new concepts for standard mechanical components or completely new components. In this scenario Metal Additive Manufacturing (AM) brings a natural competitive advantage for time-to-market contraction of new ideas and for the development of innovative solutions. Each specific application has several critical to quality requirements connected to the material choice. For new materials an alloy specific AM process development is required. The development of more efficient and functional-integrated powertrains combined with AM design freedom suggests the opportunity to develop specific AM steel grades able to withstand high wear and loads in combination with functional integration and weight reduction.

Relying on these needs the AM process setup for 20MnCr5 case-hardening steel has been investigated. Optimized AM process parameters have been identified through an extended DOE supported by microstructural analysis and mechanical testing. Particular attention has been paid on the internal residual stress management to minimize the stock-material and so the CNC machining post process. The case-hardening process has been developed focusing on standard requirements of surface hardness and case-depth profile. Considering mechanical testing several critical production variables (building directions, pre-heating during the process and stress relieving heat treatment post-process, case hardening and surface finish) of AM have been explored via tensile testing and hardness measurements. A fatigue testing plan has been designed with a DOE approach able to show main effects and interaction effects of process parameters on dynamic material behavior. Fatigue has also been investigated on a reference gear design. The collected data represented the essential starting point in the design process of the discussed case-study.

Based on the new developed material, new opportunities did open up for functional integration and, till now unthinkable design solutions for specific parts. Porsche Engineering investigated how to implement the new material in components of e-drive powertrains. Among various use cases one shall be shown here in detail. With the use of a high

sophisticated metal material usable for gears the unification of one of the heaviest components in the transmission was chosen to be designed, tested and analyzed. Using the technique of structural optimization in combination with Metal Additive Manufacturing and 20MnCr5, a unique design of the differential incl. ring gear was developed. With this combination a weight reduction of the component as well as a stiffer shape of the gears was achieved. The project did show a high potential to use the new material – development combination for specific applications which demand light weight and/or have a critical time schedules. AM technologies today enable this design for high performance applications in racing or high performance cars. With increasing productivity of AM technologies and the development of hybrid production the area of application can be extended to series production.

Introduction

Based on the use of additive manufactured plastic gears for lubrication tests in an early development phase, the idea of using the same technology for real running metal gears in prototype transmissions was born.

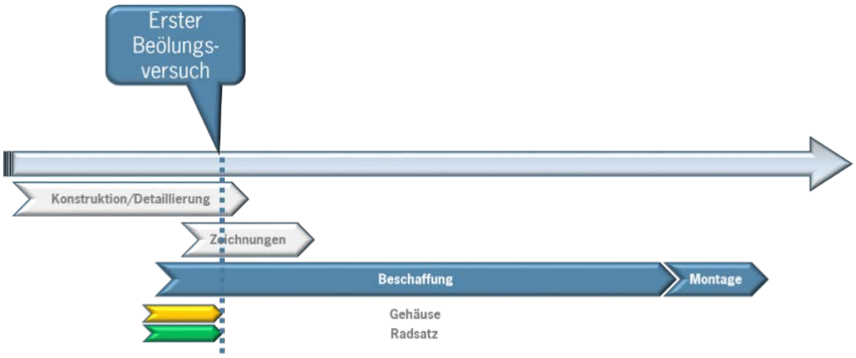


Figure 1: Timeline for transparent transmissions for lubrication tests

Figure 2: Transmission for lubrication tests with RP plastic gears

The material and manufacturing methodology should be capable of loads of at least 80% of the conventional manufactured gear. But at that time no sufficient material for rapid prototyping was available. Tests with existing metal powder materials did show a limit of 40 to 50%, which was not acceptable. GKN and Porsche Engineering discussed the topic and the necessity of a powder and production process development was identified. In this cooperation, GKN had the part of developing a powder which has the potential of withstanding all outer physical loads and develop a suitable Additive Manufacturing process whereas Porsche Engineering took the part of designing and calculating a specific part to demonstrate the potential of the metal powder and methodology.

Besides the advantage of the reduction of time to market, Metal Additive Manufacturing technologies can enable innovative design opportunities to address key performance content, like:

- Part weight reduction
- Part added functionalities
- Part increased stiffness

To be able to fully explore these design opportunities, considering the complexity of metal AM, all optimization domains should be integrated during the Project early development. This involve accurate materials selection, technology parameters optimization, 3D modeling/calculation and finally part post processing.

Focusing on laser powder bed fusion technology, several different alloys are currently available on the market with well-developed process parameters and post processing solutions. Considering iron-based alloys, two most important families of steel could be identified:

- Stainless steel
- Tool steel

They both address specific industry-related (Aerospace, Biomedical, Industrial) needs like high corrosion resistance and high strength, anyway there is an evident lack of steels able to give designers different opportunities, such as:

- Moderate material cost
- Good mechanical characteristics
- High wear resistance and contact fatigue strength.

Conscious of the potential of these market needs, 20MnCr5 (1.7147, EN10084-2008) has been identified as the optimal candidate for laser powder bed fusion (L-PBF) process development.

C %	Si % (max)	Mn %	P % (Max)	S % (Max)	Cr %
0,17 – 0,22	0,40	1,10 – 1,40	0,025	0,035	1,10 – 1,30
±0,02	+0,03	±0,05	+0,005	+0,005	±0,05

20MnCr5 steel grade is a medium strength steel able to be case-hardened, commonly recognized as one of the benchmark for case-hardened gears thanks to high wear resistance, mechanical strength and performance to cost ratio.

Powder Development

The importance of controlling all the different process phases to optimize final part behavior has been considered as the Project pillar.

Powder qualification and L-PBF process parameters have been optimized in the GKN Powder Metallurgy Innovation Center in Radevormwald (DE). Post-L-PBF processing developments include stress relieving Heat Treatment and Case Hardening process set-up.

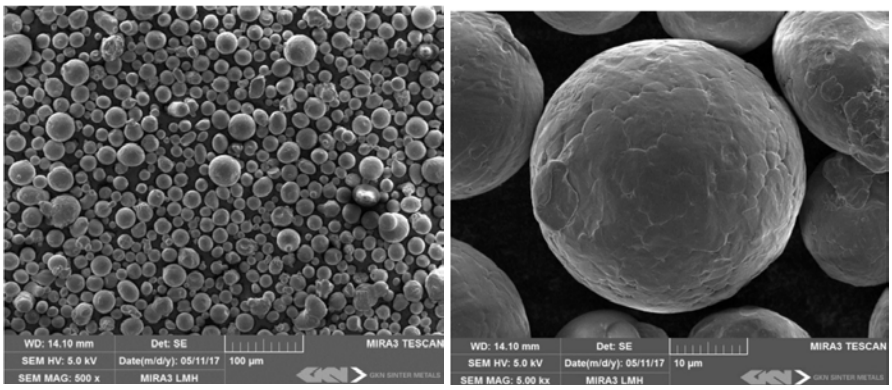


Figure 3: SEM images of 20MnCr5 powder for L-PBF

Powder spherical morphology has been confirmed trough SEM inspection (Figure 3). This powder feature helps powder flowability and so guarantees a better powder bed deposition during layers recoating.

D10 [um]	D50 [um]	D90 [um]
16,73	27,83	44,77

Powder chemical composition is within 20MnCr5 specification.

C %	Si % (max)	Mn %	P % (Max)	S % (Max)	Cr %
0,20	0,30	1,40	0,01	0,02	1,32

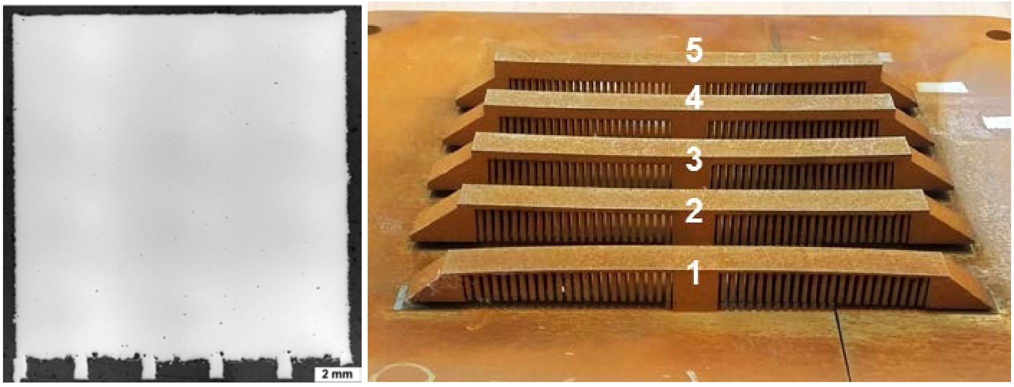
Process Development

A full design of experiment method has been used to identify the best L-PBF scanning strategy considering the most critical process parameters.

The results of each trial have been evaluated considering two critical Project KPI as:

- Process metallurgical quality.
- Process productivity.

High density of 99.95% has been achieved verified both with Archimedes method and optical analysis of metallurgical cross sections (Figure 4 a)).



a) b)

Figure 4: a) Microscope image of cross section of test sample, b) Twin cantilever for internal stress analysis

After process development using test samples high internal stresses developed by the layer-wise melting and solidification of each laser scanned layer when producing higher volume parts.

These internal stresses result in part warpage after cutting the part from the building platform.

Internal stress mitigation needs to be addressed during L-PBF process development.

In general, there are two possible approaches that can be used to manage internal stresses in L-PBF:

- Stress prevention: during the building process, with optimized scanning strategy or using build platform pre-heating results in reduced internal stresses.
- Stress reduction: after the building process, through specific stress relieving heat treatments.

In this work, the second approach has been considered since the pre-heating maximum temperature normally possible in L-PBF machines is too low for stress reduction in iron-based alloys. Still the effect of the maximum pre-heating temperature (170°C) is analyzed.

A semi-quantitative method has been used to evaluate internal stress magnitude inside the material subjected to different process conditions (building process + post heat treatment).

The used method is the Double-Cantilever approach as shown in Fig. 4b). Five different bars with a thickness of 1, 1.5, 2, 2.5 and 5 mm has been printed on the same building platform and subjected to the same process and post process conditions. This procedure would like to collect as much as possible data regarding internal stress build-up considering also cantilever thickness.

The Internal Stress Matrix is shown in the table below.

Condition	**ID**
As-build with no pre-heating	A
As-built with pre-heating 170°C	B
No pre-heating + stress relieving 1	C
Pre-heating 170°C + stress relieving 1	D
Pre-heating 170°C + stress relieving 2	E

The output of all the tests is the maximum deflection of the cantilevers measured with a CMM contact system.

The strongest effect in distortion can be seen with higher cantilever material volume. Therefore analysis of the results focus on Cantilever 5. The results are shown in Figure 5.

Several conclusions can be drawn:

- Double cantilevers method is affected by the fact that the base-plate cut is done in a subsequent moment from one side to the second side: the second side is affected by a lower curling and this effect is more evident with thicker bars.
- The pre-heating of 170°C can give some beneficial effects on internal stress reduction. This could be related to a soft tempering effect on 20MnCr5.
- The impact of pre-heating when followed by stress relieving HT can be neglected.
- The developed stress relieving temperature cycles (D+E) are both able to minimize internal stress before base-plate cutting.

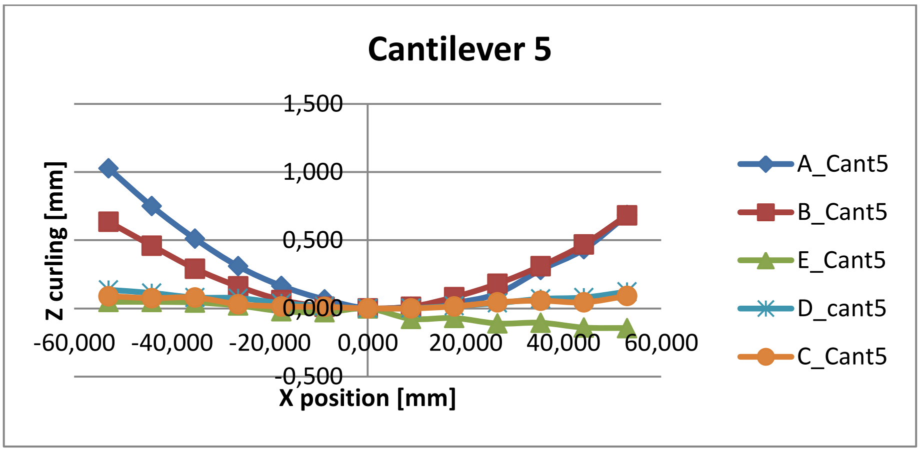


Figure 5: Results of Twin cantilever 5 measurement for different thermal treatments

Mechanical properties

Tensile strength of 20MnCr5 has been tested in different conditions. Three different metallurgical conditions have been evaluated:

- As build with no-preheating (condition A)
- Pre-heating @170°C (condition B)
- Pre-heating @170°C + stress relieving (condition C)

The effect of surface finishing has been included in the testing Matrix. Figure 6 shows the results depending on build orientation (V-vertical, H-horizontal) and surface finishing (FM-fully machined, SB-sand blasted).

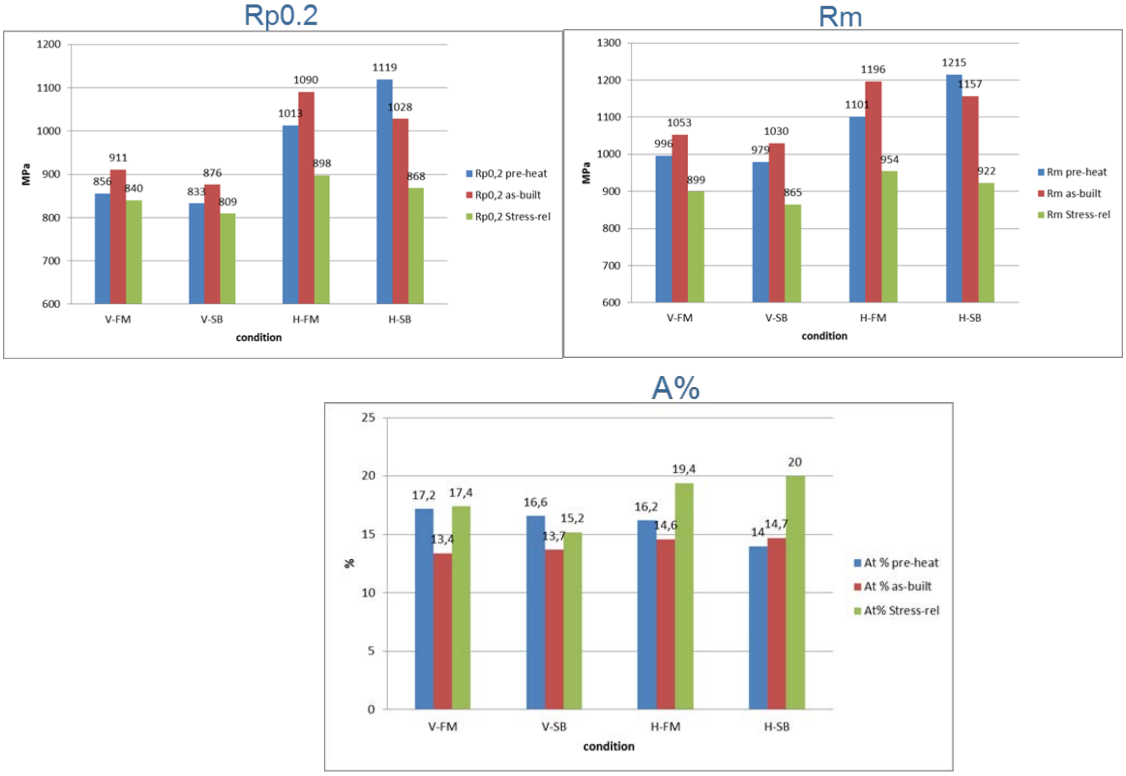


Figure 6: Mechanical properties of AM parts with different heat treatments

A direct comparison with 20MnCr5 from bar is not fully representative as 20MnCr5 static performance is strictly linked with heat treatment parameters (austenization temperature and duration, quenching media, tempering temperature and duration).
From the data in Figure 4 several conclusions can be drawn:

- The material anisotropy is clearly confirmed in the as-build condition.
  With stress relieving the material anisotropy can be reduced.
- As expected the surface finishing has no significant effect on the tensile performance of material.
- Stress relieving of 20MnCr5 leads to tensile strength reduction and elongation improvement. This is linked to internal stress reduction since the Stress Relieving temperature is considered too low to allow microstructure coalescence (Hall-Petch).

The shown mechanical characteristics of 20MnCr5 are comparable with medium strength mechanical parts normally produced by casting or CNC milling.

Tooth Root Fatigue Tests of 3D Printed Gears

Having shown the material and process development for the additive manufactured case hardening steel 20MnCr5, further opportunities to shorten the delivery time of transmissions are given. For example, lubrication runs with metal gears or first test drives can be done at a significant earlier stage of the development cycle.

Within this study, an initial technology assessment for AM produced gears has been carried out. Target of the investigations was to give a first indication of the tooth root strength of an AM prototype gear compared to PM or conventional steel materials. For these investigations, the GKN test gear (“GSM gear”), a standard test gear for all in-house available PM process routings was used.

Figure 7 shows the gear data for the GKN test gears with the achievable core and surface density levels of GKN’s powder metal processes. As initial guideline for selecting the best PM processing route for a given application, GKN has created a gear performance guideline, shown on the right [1] [2] [3].

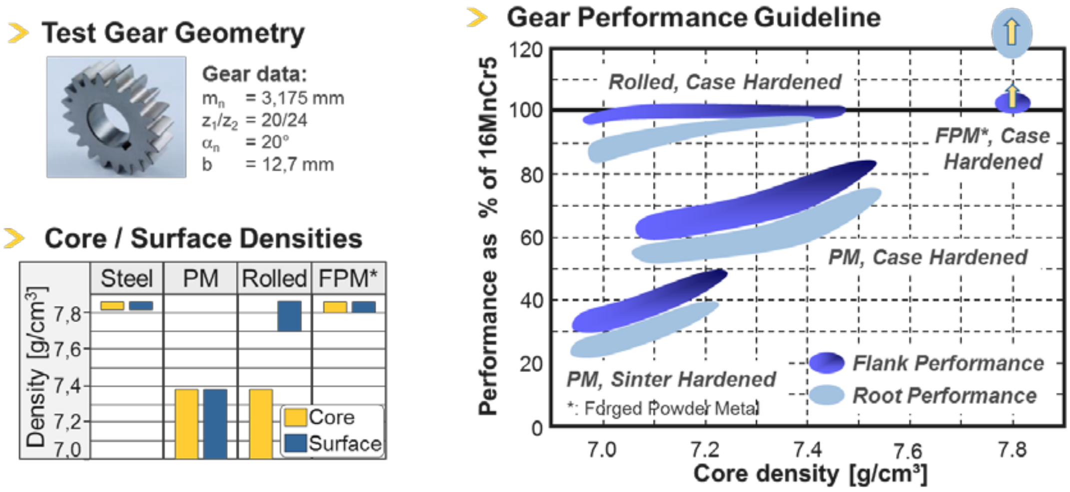


Figure 7: Gear performance guideline for today established PM processes

Figure 8 (top left) shows the 3D printing process and charging lot for the low pressure carburizing of the AM test gears, with the gears placed in the middle section. As shown by the hardening curves, the AM gears achieve the required hardening depth for the tooth flank, but showed lower values for the tooth flank section. It is also evident from the graphs that the core hardness of the AM printed gears is around 90 HV lower than the 16MnCr5 wrought steel reference gears. However, knowing that further optimization of the heat treatment process will be required and is currently ongoing, the team decided to finish grind the tooth flank of the test gears and execute first tooth root performance tests on a 50kN Rumul Testronic resonance pulsator. The initial test results indicate the potential of the AM processed and low pressure carburized gears to meet current 16MnCr5 medium steel quality level. However, it is also evident from the figure that the scatter while evaluating the 50% failure probability is higher than expected.

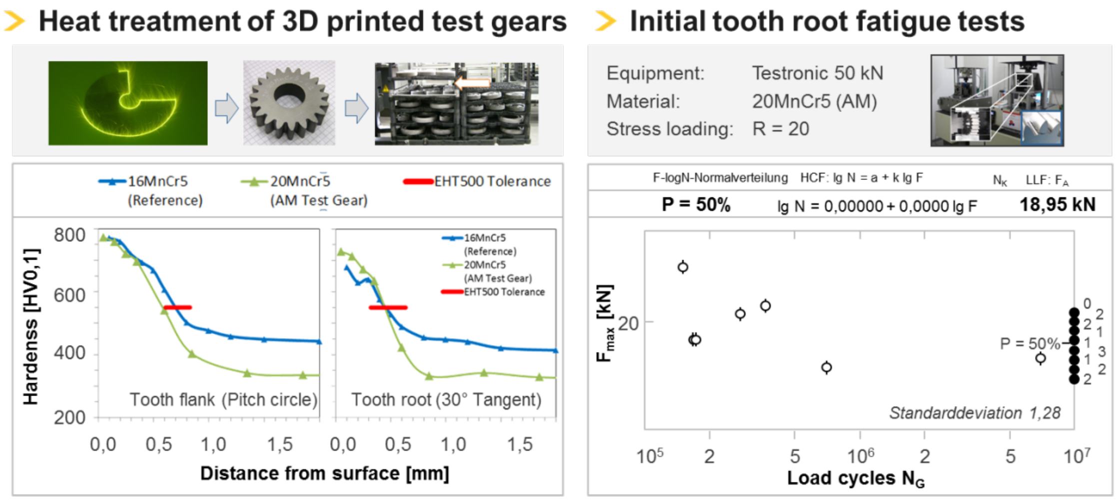
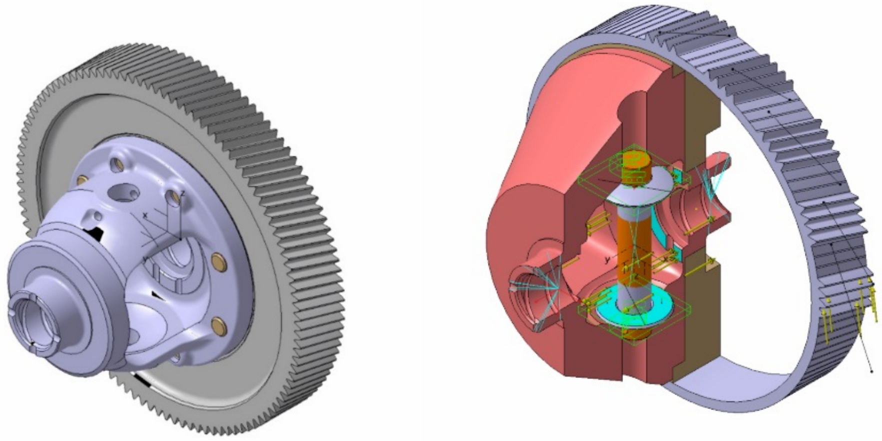


Figure 8: Heat treatment and initial tooth root fatigue tests of AM test gears

Application

To generate an optimum use of a new and innovative powder, it is mandatory to implement all advantages in the design. A simply substitution of a conventional part by an additive manufactured part will lead in higher cost and longer manufacturing time. The integration of functions and minimizing of used material can substitute these disadvantages by far.

To validate the potential of the new powder and methodology a conventional front transverse transmission was analyzed. Various components were analyzed and identified to be optimized, such as shift forks and idler gears. To achieve an optimum benefit the part with the biggest weight reduction potential was chosen – the differential housing with the ring gear.



a) b)

Figure 9: a) Conventional differential of front transverse transmission, b) package model of differential

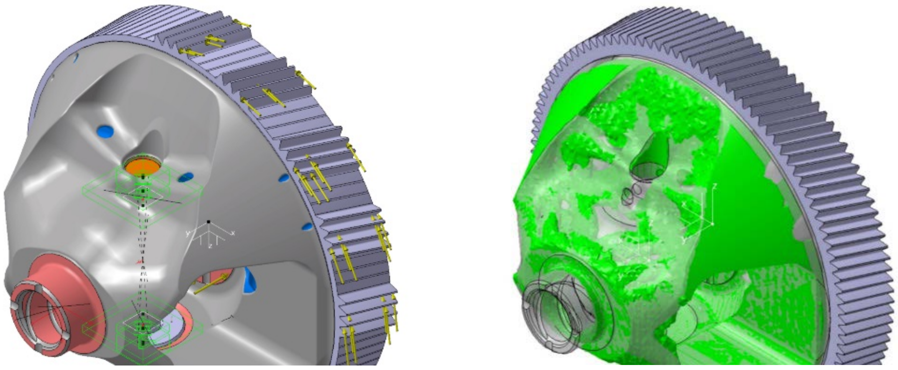
In conventional transmissions the ring gear and the differential housing are separate parts with different attributes. The ring gear made of specific steel, hardened and grinded for maximum preciseness. The differential housing normally casted for torque transfer from ring gear to center bolt and bevel gears. Due to manufacturing processes and assembly reasons the wide ring gear teeth are supported by a thin, sometimes off centered disc, which is connected to the differential housing.

Using the technology of generic structural optimization a new shape that follows the forces and not the tools was designed.

To achieve the optimum potential a model for the maximum available space inside the transmission was defined. All inner contours which are needed by any function (bevel gears, side shafts, bearings…) were subtracted of this body (Figure 9 b).

Based on the specifications and requirements of the transmission, all loads (bearing and gear) were applied to the package block. The optimization tool delivered a structure capable of taking all required loads.

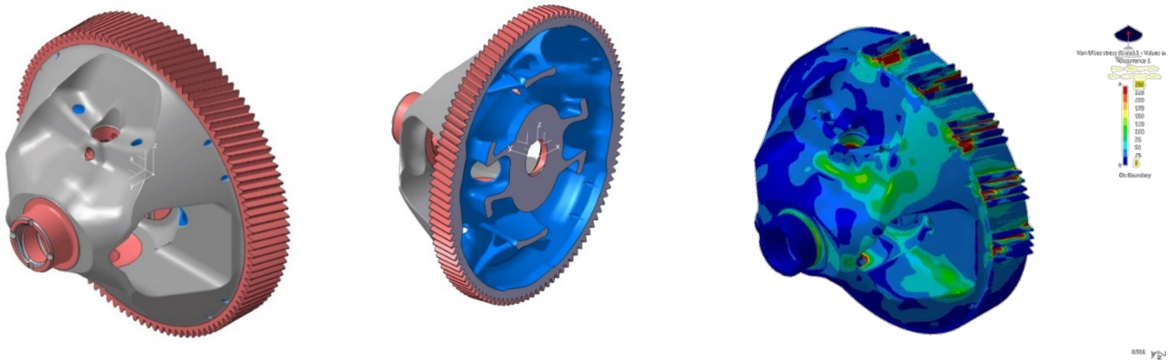
The resulting optimum structure is not producible with conventional tools. Based on the additional degrees of freedom of the additive manufacturing the possibility of realizing the product close to the calculated structure becomes possible.



a) *b)*

Figure 10: a) Loads on component, b) Cloud of points representing the force flow

By overlapping various load cases and rotating the differential in steps of 22,5 degrees, the revolting forces of the gear were represented over the circumference of the ring gear. Based on the resulting complex cloud of points a 3D CAD model was designed by respecting the new possibilities of the additive manufacturing method. Due to this fact the differential could been designed as a hollow part with a wall thickness of 2 mm.



a) b) c)

Figure 11: a) Structural optimized differential, b) Inner structure of differential, c) FEM result of differential

The inner shape is supported by a system of organic beams and structures that are only in the position necessary and not defined by possible machining. The new manufacturing process also demands special features such as holes to eject the unused metal powder after manufacturing process. Also openings on the outer diameter are necessary to have the opportunity to drain oil which will be collected in the inner area of the differential.

The final FE analysis did show a very homogeneous stress level and would also allow to decrease the wall thickness which is not possible due to machine limits.

Based on the original load requirements, the calculation shows a weight reduction of more than 13 % which means about one kilogram and a decrease of tooth stiffness variations in radial direction of 42,5 % and in tangential direction of 69,4 %. Also a reduction of the inertia of 8,1 % was achieved.

	Optimization Differential A88							
	Stresses		**Tooth-stiffness variation**		**Mass**			**Inertia**
	differential	hole front	radial	tangetial	differential with gear	bolt	total	rotating axis
	v. Mises Stress					8xM12x22		Inertia
	MPa	MPa	[mm]	[mm]	[kg]	[kg]	[kg]	[kgxmm2]
A88-CAD-STATUS	313		0,024	0,041	7,533	0,296	7,829	45634
OPTIMIZATION	183	153	0,014	0,013	6,807		6,807	41942
Changing [%]								
A88-CAD-STATUS	100%		100%	100%	100%		100%	100%
OPTIMIZATION	-41,5%	-51,1%	-42,5%	-69,4%	-9,6%		-13,1%	-8,1%

Figure 12: Calculation results

Summary and Outlook

Using the additive manufacturing process in combination with the new developed powder lead to a significant optimization in weight, inertia and stiffness of the defined part. This was possible by integrating functionalities and combining primarily conflictive components.

The simulation results show a potential of reducing weight (>13%) and inertia (>8%) and fulfilling all load requirements of the original part. This means a replacement of the serial production part seems to be possible and could be used for small series or high performance applications.

The next steps will be to validate the hardening process, final machining and testing. As part of an initial technology assessment for 3D printed geared products, first tooth root strength tests of 3D printed and low pressure carburized GKN standard test gears have been carried out. The initial results of the still ongoing test series indicate that the material has already today the potential to meet the tooth root strength of medium quality case hardening steel. However, the scatter evaluated for determining the 50% failure probability was higher than expected and further optimization work has already started. To complete the holistic gear performance assessment for the transmission and gear designers, further tests to evaluate the flank load carrying capacity (pitting resistance) of 3D printed AM gears will be carried out in the near future.

The system of appropriate material and matching process opens a very wide range of possibilities for future component design. Integration of functions, optimization of structures and minimizing of material use will lead to lighter, more stable and designed to the point parts. The Additive Manufacturing process is in a very rapid development phase. More materials will be qualified and the overall productivity of machines is increasing from year to year. This will enable the transition from prototyping applications to small series production even in cost sensitive markets.

Literature

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