Engine Timing Geartrain Concepts and Proposals for Gear Rattle Noise Reduction in Commercial Vehicles

Master of Science Thesis in the Master Degree Programme, Automotive Engineering

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Cover: Volvo engine timing gears. See chapter 4.2 for more information.

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Abstract

The engine timing gears which govern the camshaft and injection are a vital set of components in an engine and are constantly subjected to heavy loads. In recent years, imposition of firm emission legislations has forced engineers to increase the injection pressure which has a severe impact on the geartrain noise. Noise from the geartrain, distinctly gear rattle has been a main concern for the truck industry. Additionally, Volvo Powertrain also wants to focus on developing future geartrains that can be optimized from a noise point of view to meet the noise legislations. The aim of the thesis work was to propose future engine timing gear concepts for the Volvo 11, 13 and 16 liter engines. The concepts proposed are from a material selection and a layout optimization perspective. It is also focused on lowering production cost, weight and assuring sustainability. All the concepts are deduced with the main goal to reduce geartrain noise. It was found that the material choice had an influence on the component weight and adds certain valuable physical properties. The choice of material also offered a potential for cost reduction linked to its manufacturing process. Moreover, the current Volvo geartrain layout was shown to have a scope for improvement. Various layout considerations are proposed for the optimization of the geartrain based on available research in the field. For further analysis a detailed competitor benchmarking had to be conducted to study other existing geartrains and the technology utilized. The ideas from the competitors were listed and studied in order to analyze the competitive heavy duty market trend. It was found that several technologies proposed for noise reduction have been implemented by competitors to Volvo. The benchmarking study gave an insight on the current and future timing geartrains.

The task was diverse in many fields of technology, with limited boundaries. Thereby a structured and systematic approach had to be followed to cover the vast topics and deliver the result. The proposed solutions based on material, layout and recent developments in power transmission technology could have an immense potential to reduce noise. The conclusions that are drawn from this pre-study sets a platform for the development of future timing gears.

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Acknowledgements

The twenty one weeks of the project have been a good learning experience for us. We are very fortunate to have been a part of Volvo Powertrain, a part of the world's second largest heavy duty truck brand. We would like to thank our supervisors MSc. Henrik Bechtel and MSc. Sigrid Hammarquist for giving us the opportunity to be a part of Volvo Powertrain. We would also like to express our gratitude towards our supervisors at Volvo and the people helping us throughout the thesis work for their support.

Finally, we would like to acknowledge and express sincere gratitude to our supervisor at Chalmers, Prof. Associate Magnus Evertsson for advising us to find solutions in difficult situations and guiding us systematically throughout the whole thesis work.

Chalmers University of Technology, Gothenburg, May 2011
Milad Esmaeli
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1 Introduction

Volvo Powertrain which is a subsidiary of the Volvo Group is focused on research and development of the complete driveline. Volvo Powertrain is responsible for development and production of heavy engines, gearboxes and driveshafts. The production facilities are located in Sweden, France, USA, Brazil, India and Japan. Volvo Powertrain has more than 9000 employees. The thesis work was performed in the Base Engines and Materials department in Volvo Powertrain in Gothenburg, Sweden.

1.1 Background

The rapid development in the commercial vehicle industry is governed by standards set by different legislations. A concern for the environmental impact of the transportation industry has led world leaders to develop common directives for controlling pollution.

In recent years, the increased demands from emission legislations have driven engine developers to increase injection pressures to extreme levels. Current Volvo engines use an Electronically Controlled Mechanical Unit Injection System (MEUI) in which the fuel pressure is built up using power taken from the crankshaft via the timing geartrain. The increased pressure in the EUI system leads to a drastic increase in the noise levels produced from the engine geartrain and is the main noise inducing factor. Volvo Powertrain aims to reduce the geartrain noise created from hammering impacts due to gear rattling and also want to develop ideas for future engine geartrains from a noise, weight and cost perspective.

The type of injection system plays a vital role in inducing the noise in the geartrain. Due to the legislations demanding reduction in noise level produced from the engine as well as the vehicle on the whole, solutions are needed to abate the noise created from the system. The European Commission (EC) has adopted the directive 2002/49/EC (see [98]) with an aim to gather information and evaluate the extent of the noise problem within Europe. The directive will aid in the development of long-term strategies for reducing the noise levels in urban areas and in places where the population is subjected to unhealthy noise levels. Noise maps are produced which shows the noise levels of the most affected areas in the major cities. With these maps the EC can make action plans for future noise legislations and is aimed to be implemented from the year 2013. Noise legislations were adopted for road transport vehicles the first time in 1970. The EC implement the directive 70/157/EEC which limited the noise levels for road transport vehicles. Since then it has been modified nine times. The latest change was made in 1996 (COM (95)647) where the limit was set to 80 dB for heavy duty vehicles. This is the maximum limit for heavy duty trucks presently, until the new legislations come in 2013. This implementation of legislation in the future has forced the commercial vehicle industry to focus on reducing the noise generation.

The goal is to suggest alternative future timing geartrain layouts and solutions with respect to the noise, weight, cost and on whether it is possible to manufacture a particular concept. The main source of gear rattle is believed to origin from backlash in gears. A solution in order to solve this issue is further discussed. There are many technologies discussed in order to resolve the issue of backlash and there are ideas provided for future concepts and layouts of the timing geartrain.

The perfect choice of material for the timing geartrain is very important. The materials suitable for the timing gears were studied elaborately. Some materials were found which are available in the market that has a potential to reduce noise in the gears. Moreover the weight and cost concept is found to be directly influenced by the appropriate material choice for the gears.

The gross weight of the geartrain and total cost can be advantageous or disadvantageous depending on the type of material and technology used in order to reduce the noise produced. The concepts and ideas stated have to be validated, calculated, simulated and tested to be proven usable.

As a leading company in a very competitive industry it is important to know ones position relative to their competitors. Competitor analysis helps the company to recognize its position in the market and continuously develop in order to maintain and set high standards.

1.2 Objective

The objective of this thesis was to propose two to five engine gear concepts and methods to reduce gear rattle induced noise from a theoretical perspective with respect to geartrain layout, available materials and state of the art technology. The concepts and methods proposed were evaluated with respect to weight and cost factors.

A detailed competitor analysis was also performed in order to provide an insight into the current and future market trends.

In order to meet the upcoming demands on noise emissions from the engine gear train the problem at hand had to be well understood. The purpose of this work was to do an extensive research regarding possibilities to reduce the gear rattling phenomenon that occurs in the timing gears. The research also involves the possibilities for improving the layout, weight and cost of the timing gear system for future development.

1.3 Limitations

The limitations of the thesis were as follows;

- Timing chains and belts are ruled out owing to lifetime issues
- It is only a conceptual and a theoretical study
- Only gear rattle phenomenon was considered
- No measurements and physical testing is conducted
- No modeling, simulation and analysis of the proposed concepts were made
- The geartrain noise being produced from tooth deformations i.e. gear whining or any other source of noise is not dealt with

2 Methodology

The thesis involved extensive theoretical research. Extensive research data has been gathered through journals, technical papers and books. The data had to be collected in order to implement and develop new ideas for concepts. Since no calculations or simulations were conducted, the results can only be based on theoretical data and experiments previously conducted. Interviews and meetings were conducted with people from Volvo Powertrain who were experienced and specialized in many fields in order to clarify doubts and technicalities about specific parts of our task. Product information and specifications were collected by contacting companies. This was done in order to know the current specifications and properties of the product in the market. Meetings with other company personnel were also conducted in order to get guidance in the area of their expertise.

A competitor benchmarking was conducted and the data was collected to compare them to the existing Volvo solution. This was used in order to note the advantages and disadvantages in the comparison to the Volvo timing system. The information collected has been relying on the benchmarking studies done earlier and the hardware available in-house for examination. A great amount of data has also been possible to gather through benchmarking databases. The benchmarking database used in this benchmarking study is; “A2Mac1” [91]. Full teardown reviews are made here and some basic information is provided about the different components. Some more information regarding the competitors has been gathered via patents available in databases. Benchmarking information was also collected by having meetings with people responsible for competitor benchmarking at Volvo Powertrain. The knowledge from previous years in development and the current direction of the market can be much better viewed by an experienced person.

A structured approach was followed to meet the objective of the thesis. Since the task was very diverse into many fields a structured approach had to be adapted in order to be within the desired scope. The first step was to define research questions. The research questions were used as guidance throughout the work in order to fulfill the purpose of the thesis. A question-answer approach was used to introduce the problem as well as clarify the conclusions drawn from the thesis. This had a great influence in the gathering of information and the way the report was written and formed. The basic idea was to form the report in such a way that the diversity of the different fields the work would be involved with would be presented with a question to justify its meaning in the work. From this approach the relatively large theoretical chapter would also come to use by aiding in the understanding of the answer given to the stated question.

A free Windows application called “Free Mind” was used in order to deduce a mind map (see appendix 1.1) listing the fields and its subdivisions within the scope of the task assigned. All the research data is graphically summarized in the mind map to provide an overview of important points to keep in mind while developing a concept. A mind map is a good way of having a holistic view during the “brainstorming” part of the work. This helps to gather ideas in one place and categorize them for further analysis. The mind map also gives people outside the project a good perspective of what ideas have been thought of and in what direction the work is heading. The work could thereby be guided into other ways of thinking with a structured approach. Ideas that have been excluded should also be kept here for future reference.

In order to identify concepts for a future geartrain and in order to reduce noise across the geartrain "out-of-the-box" thinking and in depth brainstorming had to be performed to come up with solutions and validations. To provide a good visualization of the proposed concepts, Autodesk Inventor 2011 was implemented for modeling.

3 Research questions

In this chapter the research questions that were stated in the project will be described. These research questions are stated to clarify the main goals of the project and ease the verification of whether the purpose of the project has been fulfilled. In this stage of a concept development process the need for research questions is essential in order to in a structured way be able to cover the rather vast number of factors involved. The project has been divided into six main topics which are correlated.

Noise related questions define the most general and relevant issues related to the geartrain noise:

- Which are the main sources of the noise generation?
- How is the current injection system affecting the noise generation?
- How can gear rattling noise be reduced?
- What technologies exist for reducing the noise?
- Does the material choice influence noise generation?

The design layout related questions involve the gear layout used to transmit power and motion from crankshaft to the camshaft. The questions relate to the position of the gears and components:

- Does the layout and relative position of gears have an effect on the noise level?
- Does the number of meshes have an influence on noise?
- Is it possible to use bigger gears (with larger diameter) to reduce the number of meshes from a noise-reduction point of view?
- What possibilities exist for alternative power transmission systems?
- What impact does an alternate layout have on cost?

Material and manufacturing related questions involve alternatives for steel as a material in the gears. The benefits and limitations related to these materials are considered.

- What materials and manufacturing alternatives to steel exist that are possible to use for heavily loaded gears?
- Do the alternate materials provide better internal damping properties?
- Can the material behavior be simulated with available softwares?

Weight reduction related material questions and possible parameter changes for the whole geartrain to be lighter are formed with a wide perspective:

- Can the weight of the geartrain be reduced by the choice of material?
- Can the design of the gears be changed to save weight?

Cost related questions are very general and mostly concerns obvious factors pertaining to cost:

- How can cost of the geartrain be reduced?
- How does the manufacturing process facilitate cost reduction?

Competitor benchmarking questions are related to information about current competitor technologies:

- How are companies proceeding concerning to noise and cost related to geartrains? What are their plans for future development?
- Have any of the patents filed been put into production?

4 Theory

4.1 Gears

There are many types of gears available which could be used to transmit power seamlessly and synchronously in the geartrain. These types will be discussed in this chapter. The normally used gear types and geartrain technologies used are explained.

4.1.1 Spur gears

Spur gears or straight cut gears have involute teeth profiles without any angling to the axis of rotation as shown in Figure 4.1. They are only used to connect parallel shafts. Spur gears are commonly used owing to lower cost but with a compromise of noise. This type of gears produce a lot of noise while operation and moreover has a stress concentration on the point of contact on the driving side of the gear teeth. Spur gears are not a suitable option for applications which demand high loads, because it has a smaller surface area. [1] [78]

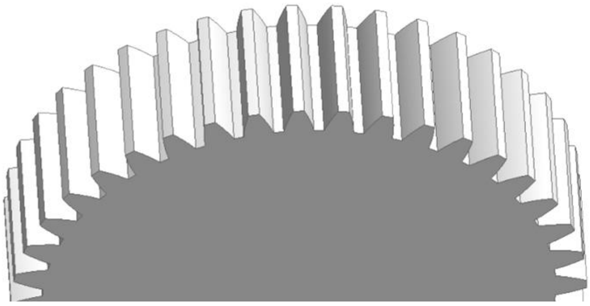


Figure 4.1: Spur gear

4.1.2 Helical gears

Helical gears are gears whose involute is cut at an angle to the axis of rotation as shown in Figure 4.2. This angle is referred to as the helix angle and differs for different gears depending on the application. Helical gears can be used to connect parallel or a non parallel shaft. This type of gear is comparatively silent and operates smoothly compared to spur gears because of higher contact ratio. Moreover the stress is transferred from one end to the other end of the driving gear teeth preventing pitting on the teeth. Helical gears have a possibility to withstand higher loads because of greater surface area in contrast to spur gears. Amidst its advantages, these types of gears are relatively expensive to manufacture. They also produce axial thrust while operation, hence thrust bearings are needed to take up axial loads. [1] [78]

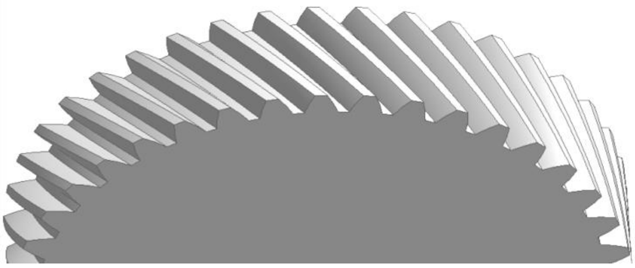


Figure 4.2: Helical gear

4.1.3 High contact ratio spur gears

High contact spur gears are like normal spur gears but the meshes has a higher contact ratio. Contact ratio is defined as a measure of the average number of teeth in contact during the period in which a tooth comes and goes out of contact with the mating gear relative to the pitch. The contact ratio for a general spur gear is around two, if the contact ratio for spur gears is greater than two then it is referred as high contact ratio spur gears. Increasing the contact ratio of spur gears has proven to reduce noise and also have better performance. One major drawback of high contact ratio spur gears is that it produces gear whine at higher speeds. [78]

4.2 Geartrain

The engine timing geartrain is one of the vital set of components in the engine. It is used to transfer power from crankshaft to the camshaft and to maintain the valve timing in the engine. Hence, power and rotational motion from the crankshaft to the camshaft has to be transferred constantly without any abruptions for the engine to function properly. Timing of the engine can be maintained by gears, belts or chains. The majority of medium and almost all heavy duty engines have timing gears owing to its capability to withstand higher loads and since it has higher longevity compared to belts and chains. [2]

The valves (and/or injectors) can be driven directly by an overhead camshaft or through a pushrod system. The Volvo engine uses a single overhead camshaft system which is also used to drive the mechanical unit injectors. The geartrain of a Volvo 13 liter engine is shown in Figure 4.3. The main layout of the gears from the crankshaft to the camshaft is depicted in dark grey. The geartrain is also used to supply power to other auxiliaries like the water pump, air compressor, oil pump, power take off (PTO). The auxiliaries can be seen in Figure 4.3 and are depicted in yellow. [2]

The power is taken from the crank gear to the cam gear by a set of idler gears. The crank gear is press-fitted on the crankshaft. The periodical torque variations from the combustion process cause torsional vibrations in the crankshaft and should be isolated from the rest of the system. A viscous damper is placed on the front end of the crankshaft to abate the propagation of these vibrations to the crank gear. The bull gear is the largest gear in the entire geartrain. It consists of two helical gears of different diameters on the same axis to achieve the desired speed ratio between crankshaft and the adjustable idler and concurrently allows for less space utilization. The adjustable idler is used to adjust to reach the camshaft and adjust the amount of backlash during production.

As mentioned previously the auxiliaries in the geartrain derive power primarily from the crankshaft and the idler bull gear. The oil pump gear is directly connected to the crankshaft and is used to pressurize oil. The steering servo pump gear is connected to the crankshaft via an idler. The bull gear drives the piston type air compressor and the PTO.

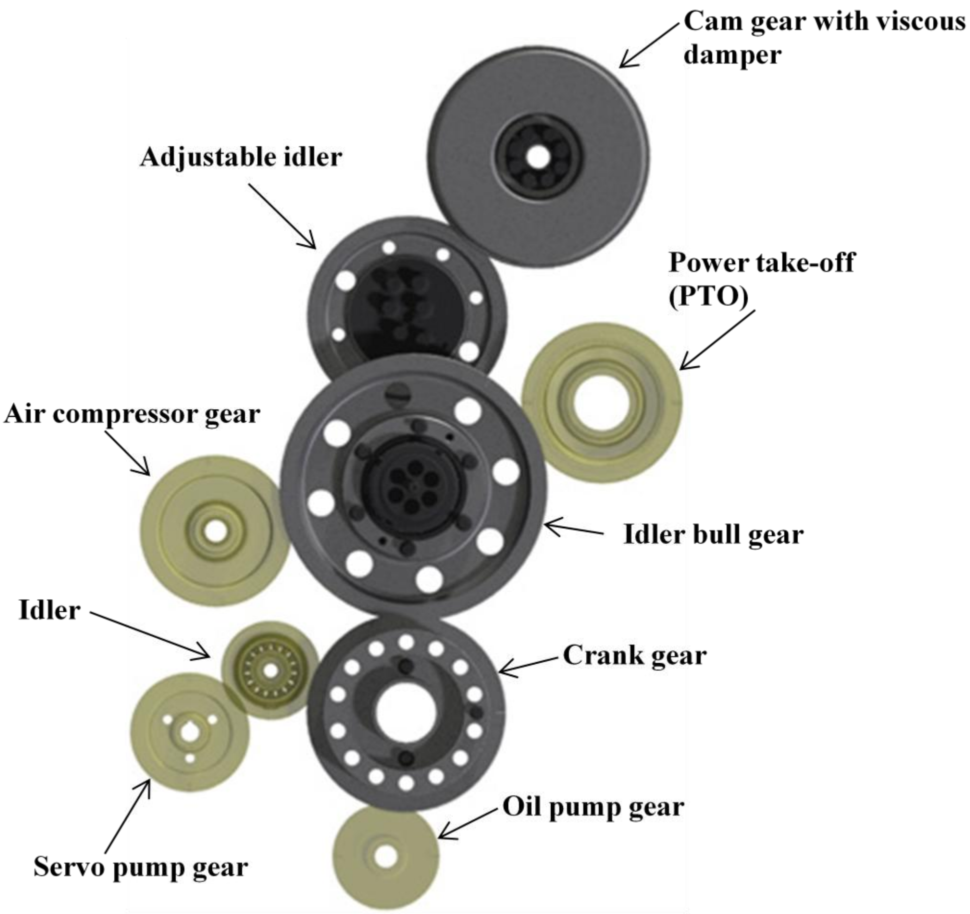


Figure 4.3: A Volvo geartrain layout

The geartrain can be placed either in the front or the rear of the engine. Earlier engines and some present heavy duty engines feature geartrain in the front of the engine. Most of the heavy duty engines have the timing gears in the rear of the engine. The crankshaft and camshaft positions are the main controlling factors for the layout of the timing geartrain. Additionally, the layout of the geartrain is dependent on the packaging possibilities in the engine compartment. [2]

The gears of the geartrain are mounted on shafts supported by the cylinder block. Bearings are very essential as well in order to minimize loss of power from friction and also to ensure smooth running of the gear. The bearings are mounted between the gears and the shafts. In the Volvo geartrain as shown in Figure 4.3 tapered roller bearings are used for the bull gear since it is a helical gear and it produces thrust forces. Roller bearings and plain bearings are used as well in appropriate places. [78]

Apart from the front and rear, the geartrain can also be placed in the middle of the crankshaft as shown in Figure 4.4 and Figure 4.5. The crank gear must be located on the node of the crankshaft to avoid vibrations. The node on the crankshaft is a point where the amplitude of the vibration is minimal in the crankshaft. There are engines which also feature crank gear in the middle of the crankshaft for either the entire geartrain or only for the oil pump or only for balancer shaft in some engines. [79]

Figure 4.4: Crankshaft with crank gear in the middle in Suzuki Hayabusa [80]

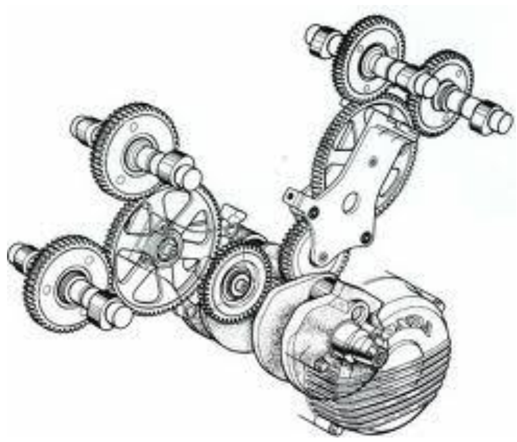


Figure 4.5: Timing gears of a Honda VF1000R [81]

Crank gear in the middle of the crankshaft has been observed only in motorcycle engines. It is possible but challenging to implement it on a heavy duty engine, since it has to bore through the cylinder block, which can be a difficult design when it comes to durability of the cylinder block and the gears as well. Lubricating the gears is also a challenge. But it could be investigated more for a concept study. Lubrication of the gears in the geartrain is very important. In order to ensure proper operation of the gears without getting jammed or overheated due to friction lubrication of the gears is essential. The geartrain is lubricated by a mist formed by supplying pressurized lubricant or oil to the geartrain in proper positions. [5]

As mentioned earlier the geartrain can be composed of helical, spur, high contact ratio or any other type of gears. A very important aspect is arranging all the gears in an efficient way such that there is no compromise on performance or packaging.

The geartrain is a source of noise generation due to motion between gears causing impacts (see chapter 4.4). It is also one of the major contributors to engine air borne noise and structural vibrations after the combustion and injection noise. There are many sources of noise and vibration generation from a geartrain, some are mentioned below:

- Gear rattle between meshing gears
- Gear whine at higher speeds
- Noise generated from auxiliary components
- Noise and vibration propagation from auxiliary components to the geartrain

The torsional vibrations can be induced in the geartrain from a number of sources. As mentioned previously, one of the main sources is from the crankshaft. Another major contributor is the opposite torque which is generated as a result of the fuel pressure that is mechanically produced. A mechanical electronically controlled unit injector system (MEUI), driven by the camshaft, is used by Volvo to create high fuel injection pressures. The fuel pressure in a MEUI system is built up mechanically for each injector. The actuation is electronically controlled. The high torques required to create the desired pressures causes angular elastic deformations and results in a spring back giving negative torques in the camshaft. The high torque fluctuations created as a result of this is transferred into the geartrain through the camshaft gear.

4.3 Backlash in gears

The backlash is the clearance or the gap between the gear teeth after meshing (see Figure 4.6: Backlash in a mesh [81]). Backlash cannot be avoided and is essential in gears to prevent it from jamming. At higher operating temperatures gears tend to expand and to allow for this expansion, backlash is provided to compensate for this phenomenon. Setting this backlash clearance is very crucial, it should not be too less nor should it be too much. A lower amount of backlash might result in jamming of gears, on the contrary if the amount of backlash is too large it will lead to increased gear rattle.

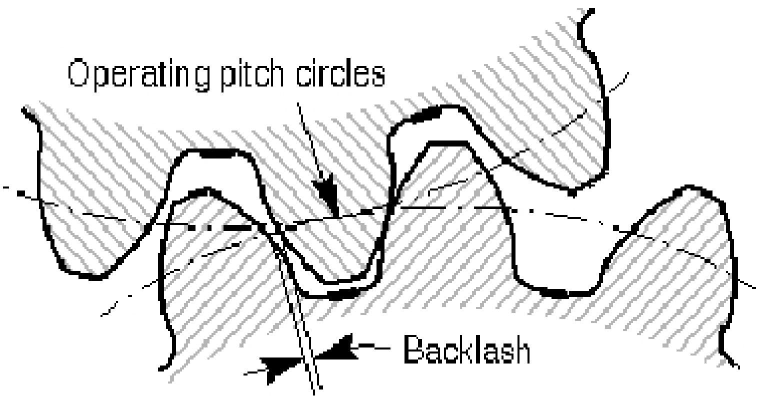


Figure 4.6: Backlash in a mesh [81]

The gear rattle motion between the gears due to backlash clearance, resulting from meshing and unmeshing of gear teeth results in creation of an impact noise referred to as gear hammering. The Figure 4.7 below shows the effect of backlash on gear rattle. It is clearly observed from the graph that lower the backlash lower will be the gear rattle, but on the contrary as the backlash increases drastically the gear rattle decreases as well. This is because there is a large gap between the teeth and hence the gear teeth will not rattle between the two teeth, but there will be larger impacts on the driving side of the gear teeth. It is observed that at an optimum level of backlash the gear rattle peaks drastically and it is not favorable for the geartrain from noise and longevity point of view.

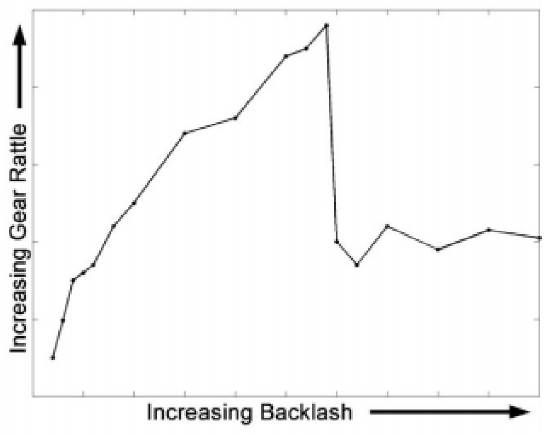


Figure 4.7: Croker's graph [19]

The gear rattle phenomenon along with methods to deduce it is discussed in detail in the next chapter.

4.4 Gear rattling phenomenon and hammering noise

Gears are designed in a way to always ensure smooth operation. A specific amount of clearance is thereby required between gear teeth in mesh (see chapter 4.3). Although, the backlash allows for an undesired "free flight" between the driving side and driven side of the gear tooth (see chapter 4.3). The fundamentals of the rattle phenomenon in vehicle gearboxes and engine geartrain will be discussed in this chapter.

4.4.1 Gearbox rattle

The main contributing factor to the unmeshing of the gear pair in an automotive gearbox is the torsional vibrations originating from the fluctuating torques created by the internal combustion engine. As the contact between the teeth is lost, the teeth move freely back and forth through the clearances and may cause multiple impacts. This phenomenon, often encountered in automotive transmissions, is known as rattling. The noise can be emitted though airborne vibrations or through the structure of the gearbox spreading to other components from which airborne noise may be emitted.

The rattling noise has in recent years been an increasing problem due to downsizing of engines, lighter parts and higher noise vibration and harshness standards. The rattling phenomenon of lightly loaded gears in vehicle transmissions has for this reason been well understood. An extensive coverage of the rattling phenomenon taking place in gearboxes can thus be found in the literature. A number of theoretical models have been developed in order to describe the impulsive rattle phenomenon. Numerous ways of reducing the rattling noise has also been proposed. An example is the dual mass flywheel which dampens the torsional vibrations from the crankshaft. A relation has also been found between the amount and the viscosity of the lubricating oil inside the gearbox housing. The drag torque created by oil resists the free motion of the gears in the gearbox preventing the initiation of the rattling motion. Hence, the effect of the oil in a gearbox is not negligible.

References: [20, 21, 22, 23]

4.4.2 Modeling of gearbox rattle

To further understand the rattling phenomenon occurring in a gearbox a theoretical model is studied. Figure 4.8 illustrates the motion of a loose part, with mass m_2, that vibrates within the backlash, s_v, of the driving gear with mass m_1. The external force R_a is the resisting force caused by drag. This is a model derived in [3] and is based on the EKM ("Einfachts-Klapper-Modell" – simplest rattling model) calculation methods. The free body can be regarded as a floating idler gear and is modeled as a rigid body. These models can be used in order to simulate loose transmission components by creating movement equations using the model parameters. A first approximation is made that the noise level is proportional to the pulse transmitted when impacts occur. The theorem of momentum and angular moment connects the force and the movement profile of the loose part. The average impact intensity I_m is thereby possible to determine as follows:

$$\mathrm{I_m} = \mathrm{m_2 \dot{\omega}_{a1} r_{b1} C_{I_m}} \tag{4.1}$$

Where the mass of the excited loose gear is m_2, $\dot{\omega}_{a1}$ is the angular acceleration amplitude, r_{b1} is the pitch circle radius of the exciting gear and C_{I_m} is the related average impact intensity for tooth flank impacts (further explained in [3]. The verdict of this model is that impact intensity, I_m, can be related to the noise level produced by rattling. The noise level of rattling, L_p, is described by:

$$\mathrm{L_p} = 10 \cdot \log\left(\mathrm{k} \cdot \mathrm{I_m} + 10^{0.1 \cdot \mathrm{L_{basic}}}\right) \tag{4.2}$$

Where the basic noise level, L_{Basic} is estimated or attained from measurements and the calibration factor k is derived from comparing a measured airborne sound pressure level with a simulated value for the average impact intensity, I_m. The calibration factor is thereby the connection between the real average impact intensity and the acoustic pressure. These calculations could help to link different factors affecting the rattle noise produced in the gearbox, and hence compare it to the rattling phenomenon occurring in the engine geartrain.

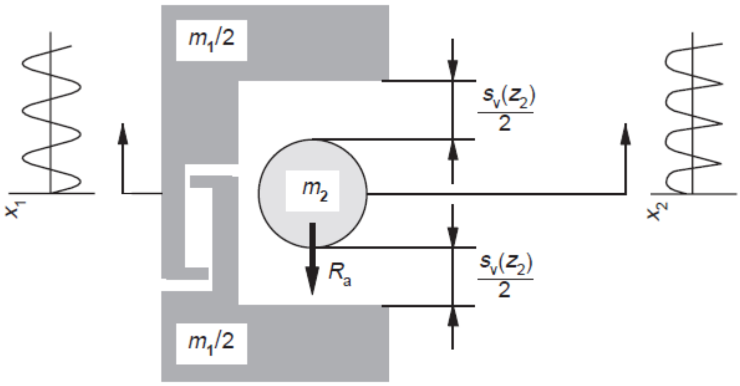


Figure 4.8: Model for backlash, s_v, in a gear mesh [3]

References: [3, 20, 21, 22, 23]

4.4.3 Engine geartrain rattling phenomenon and hammering noise

The phenomenon taking place in vehicle gearboxes is to some level different from the case in the engine geartrain. The rattling motion is still apparent as in the gearbox but additional excitation mechanisms are involved. Rattle occurring in the engine timing gears is affected by the torsional vibrations from the crank and the camshaft (see chapter 4.2), but also other factors are involved. The engine geartrain is connected to other components (see chapter 4.2) that produce periodical rotary fluctuations. Due to the nature of the forced impact (as opposed to the free motion of gears in gearboxes) between the gears in the geartrain, the noise created from these gears is mostly referred to as gear hammering as explained in [25] and [26].

The components connected to the engine geartrain create irregular tooth impacts. This has to be differentiated from the more periodical fluctuations caused by the components coupled to the combustion process. An example of periodical fluctuations is the torque variations due to injection pressure built up in the injectors in a unit injector (UI) system driven by the camshaft gear. The phasing difference between component vibrations and the engine cycles introduces this irregularity. The experiment in [24], however, shows that the periodic excitations are much more prominent in comparison to the stochastic excitations. It is these high torque fluctuations that commence the rattling in the geartrain, where high contact forces are created for a very short time between the gear teeth. It is thus clear that the rattling of the idling unloaded gears in a gearbox is different from those in the engine geartrain and has to be studied and modeled with a different approach. [24]

4.4.4 Modeling of engine timing geartrain rattling and hammering

Attempts have been made to model the hammering phenomenon. In [25], [26] and [27] the modeling of the impacts between the gear teeth in the engine geartrain of a diesel engine is investigated and modeled. Three different methods of modeling the gears were used in order to obtain a greater insight in the forces and the dynamic behavior of the gears at the point of impact. The gears are typically modeled as rigid bodies that are coupled with a spring-damper system. It is claimed that the elastic compliance, i.e. the strain/stress ratio, should however not be neglected. Moreover, static methods are used for describing input parameters, which is only valid for cylindrical gear bodies.

The three methods used in this study are; a rigid-body model, a finite element model and a fully elastic multi-body model. The rigid body model gave the fastest results, at the expense of less precise simulation results. A great contrast was seen in simulation results of the FE-model and the rigid-body model. Very precise contact forces could be achieved with the FE-model, but at much larger computational times.

It was suggested that in order to reach precise results and concurrently keeping the simulation times down a fully elastic multi-body model could be used. Modal models are used to model the elastic bodies. These make it possible to attain high precision models to simulate contact forces and the global motion of the gear wheels.

In order to determine the contacts in an efficient manner, a specific contact algorithm is used. Firstly, a coarse collision detection is made by finding the index nodes closest to the center of each gear. These teeth are then regarded as a reference (see Figure 4.9). One or two teeth on both sides of these center teeth are most likely to have contact. This increases efficiency of the contact detection, since normally only two or three teeth are in contact in a gear mesh. A master-slave node-to-segment penalty approach is used in order to achieve the fine collision detection. The node-to-segment (NTS) algorithm is the most widely used algorithm for detecting contact between non-matching meshes (see [28] for a more detailed description). The NTS algorithm is used for two-dimensional contact problems, hence only the nodes on the flank of the teeth are considered. In [27] the contact problem is simplified to a 2-dimensional contact situation, since the investigation only involves perfectly aligned spur gears. Thereby, only the flank nodes in a certain plane are necessary to be considered for the fine collision detection.

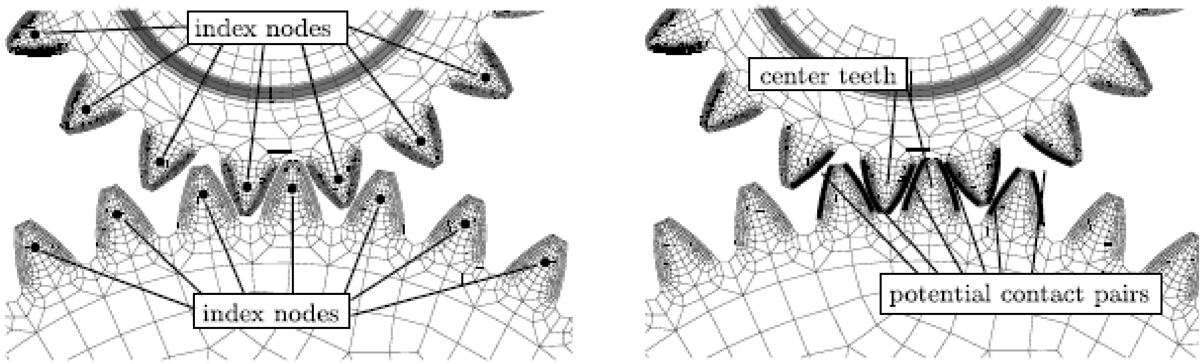


Figure 4.9: Contact simulation of a gear mesh [27]

This modeling technique shows roughly the same accuracy as the FE-model. The elastic description gives very precise contact forces due to that the depictions of the dynamic effects are made properly. Furthermore, the simulation results where validated by conducting a set of experimental investigations. It is confirmed from these experiments that the elastic Multi-body model is indeed a good way of simulating tooth impacts. [26]

One of the available softwares for multi-body simulations of the rattling behavior in gear transmissions is Romax NVH. The Romax NVH model allows for the modeling, simulation and analysis of geared transmission systems. Since gear whine and gear rattle are two noise problems often occurring in gear transmission systems, it is with Romax NVH that made it possible to consider both in the same environment and in the same model. Doing this at an early stage of the development could help improve the transmission system from an NVH point of view. This is thus made with relatively low costs compared to full scale tests. [30]

Additionally, FEV Inc. and AVL (Anstalt für Verbrennungskraftmaschinen List) are two companies also focused on developing softwares for multi-body modeling. FEV has developed a simulation method for geartrain analysis for identifying and optimizing noise sources. The method is based on a combination of multi-body and FE-models. “Excite” is the software which is available from AVL. It allows for noise and vibration assessment specifically for gear transmissions.

References: [20, 24, 25, 26, 27, 28, 29]

4.5 Noise and vibration generation

Noise is defined as the unwanted sound to the human ear. In a geartrain, noise is generated by the impact caused when one gear tooth slams on the corresponding tooth of the meshed gear. This is the impact generated only from one gear pair. Hence there will be a summation of noise that will be generated from a number of meshes in a geartrain. The sound wave generated causes a change in the sound pressure that can be measured by a microphone and the level of noise generated is obtained in decibel (dB). The sound pressure level of a single mesh to a reference value is a logarithmic measure of the effective sound pressure. [4]

Sound pressure level for one radiating source (dB) is mentioned below.

$$L_p = 10\log_{10}\left(\frac{P_{rms}^2}{P_{ref}^2}\right) \tag{4.3}$$

Where P_{rms} is the root mean square of the sound pressure being measured and P_{ref} is reference sound pressure. The commonly used reference sound pressure in air is $P_{ref} = 20$ (μPa).

In a gear train there are multiple sources of noise that is generated from various meshes in the geartrain and the sound pressure level is a logarithmic measure of the summation of all the respective values to a reference value.

Sound pressure level (dB) for *n* radiating sources is mentioned below:

$$L_{\Sigma} = 10\log_{10}\left(\frac{P_1{}^2+P_2{}^2+ \ldots\ldots+P_n{}^2}{P_{ref}{}^2}\right) \tag{4.4}$$

From the above equation 4.4, it is proven that the number of meshes is a vital factor in the design for layout of the gears. As the number of gear meshes increases the error due to backlash increases. This influences the total noise level produced from the meshes in the geartrain. Vibrations in an engine are created due to combustion forces, gear meshes, uneven friction and many more. The vibration itself does not produce noise. The vibration propagates from the engine (source) in almost all the directions from the source of generation and it is radiated as noise from the panels or auxiliary or structures which are fastened to the source. Moreover, if the fastenings are loose a louder and harsher noise is produced. [4]

4.6 Noise and vibration isolation

With the trend moving towards increasing injection pressures, there is a lot of concern with increasing noise and vibration levels. The engine cannot be made completely silent. The geartrain is also one of the major contributors of noise and vibration apart from the engine. The noise and vibration produced from the geartrain and the whole engine has to be isolated to the surroundings and to the cab. This can be done by implementing multilayer sound barriers, absorption materials (foams, fibrous blankets or acoustical ties), vibration isolators (rubber or plastic bushings, grommets or equipment mounts) and materials with damping properties. The air borne noise is mainly dealt by using barriers and absorption materials and the structure borne vibrations are mainly isolated using vibration isolators and damping materials. Utilization of noise and vibration isolating devices limits the propagation of noise and vibrations through the structure. [31] [32]

4.7 Gear Materials

The selection of an appropriate material for a gear is a very crucial decision. The material must be selected based on the mechanical properties of the material and whether the material is feasible for the particular gear application in the particular position.

For highly loaded gears, like the timing gears in heavy duty trucks, the bending and fatigue stress of the gears teeth are of highest importance. The type of load that the gears are subjected to is important, i.e. whether the load is gradually or instantaneously applied. Parts of the gear will have to handle bending, contact stress, scoring, wear and fatigue. The two primary failure modes for gears are thereby; Tooth breakage (due to bending stress) and surface pitting/wear (due to contact stress).

A gear tooth can handle a certain amount of load before it is permanently deformed. The strength (the amount of stress that can be tolerated before permanent deformation) of the material and the geometric stress concentrations in the gear are key factors for the handling of these bending stresses. The tooth root is an area where the shape and design plays a big role since it is the area where the highest stress concentrations in tension are felt. The tooth root radius also requires good surface hardness and high residual compressive stress to improve endurance, which is greatly affected by the material choice and after-treatments.

A number of different factors and properties have to be considered while choosing an appropriate and efficient material for an engine gear. These include:

- Material availability
- Cost
- Fatigue limits
- Temperature limits
- Fracture toughness
- Load and torque carrying capacity
- Manufacturing requirements
- Weight
- Treatments
- Machineability
- Operational characteristics
- Damping characteristics
- Corrosion and wear resistance

One very decisive factor when choosing gear material is the overall cost of the material and the production cost. Figure 4.10 gives an overview of the distribution of the gear manufacturing costs for the production of gears. It is realized that the cost of the material only has a relatively small impact on the total cost of the production of a gear. The costs are dominated by the heat treatment and machining costs to produce the right dimensions and obtain the right properties of the material used (in this case steel). [5]

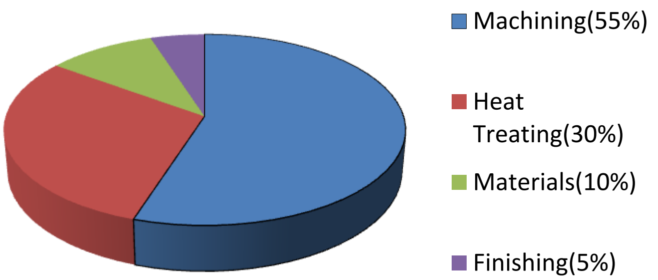


Figure 4.10: Distribution of manufacturing costs[5]

This cost distribution will vary depending on the material, manufacturing processes and after-treatment requirements.

There are a number of different materials that are possible to use for gear transmissions depending on loads and operating conditions. Gears are mostly made from ferrous metals, non-ferrous metals and non metallic materials. Ferrous metals are more commonly used for engine gears owing to its strength, its properties and heat treatment capabilities.

Currently Volvo uses precipitation hardened steel which is further nitrocarburized and case hardened to enhance the properties of helical steel gears for the engine gears with roller, thrust and sliding bearings appropriately.

Materials found and further discussed having the ability to replace steel completely is powder metal gears (with different compositions) and ADI (Austempered Ductile iron) gears. Austempered gray iron can also be used but only in situation where light loads are applied. Plastics can also be used in the future but needs a lot of research in order to resist loads and temperature. [5]

Materials and manufacturing processes discussed in detail:

- Steel
- Powder Metallurgy
- Austempered Ductile iron
- Austempered Gray Iron
- Plastics

4.7.1 Steel

Steel is the most commonly used material for Engine timing gears. Their availability and ability to combine high strength per unit volume with low cost per kilogram make them an attractive choice of material for gear manufacturing. Steels are diverse, ranging from carbon steels with varying carbon content to alloyed steels. Alloy steels are preferred rather than the plain carbon steel because of higher hardenability and the desired microstructures resulting from the hardening processes. Steel is most commonly used owing to its strength and the available heat treatments to improve its properties. Volvo uses nitrocarburized and case hardened steel for its timing gears in the 11, 13 and the 16 liter engines. [5]

4.7.2 Austempered ductile iron

Ductile iron is a type of cast iron invented in 1943. Cast iron grades are brittle. Ductile iron is much more flexible and elastic, due to its nodular graphite inclusions. In ductile irons the graphite is in the form of spherical nodules which prevent the creation of cracks and provide the enhanced ductility that gives the alloy its name. Heat treating alloyed ductile iron by austempering process results in the formation of Austempered Ductile Iron (ADI).

The austempering process involves austenitizing, quenching and cooling. In austenitizing, the material is heated and kept at a particular temperature for a specific period of time depending on the grade required. The material is then quenched at a particular cooling rate at a specific time in order to avoid the formation of pearlite. Finally the material is air cooled or in special cooling rooms.

Austempering is an isothermal heat treatment process that can be applied to ferrous materials to increase strength and toughness. ADI castings differs a lot from ductile iron castings in the composition , alloys like molybdenum ,copper, nickel are added to improve the material properties. As a result of enhanced material properties of ADI compared to conventional ductile iron, ADI is strong competitor to steels. [34]

4.7.2.1 Composition of ADI

Alloys are added to ductile iron and it is austempered accordingly depending on the grade of ADI required. Alloys are added to improve the materials properties. The alloys added and their effects are discussed below.

The content of Carbon is very vital in ADI. It can be increased within 3 to 4% to facilitate tensile strength. The effect of addition of carbon has no effects on elongation and hardness. Carbon content should be monitored within 3.6-3.8%

Silicon is a crucial alloy added to aid the formation of graphite. The solubility of carbon in austenite decreases due to the addition of silicon. Moreover, it improves the eutectoid temperature and also prevents the creation of bainitic carbide. The impact strength of ADI is directly proportional to the amount of silicon added. Greater the amount of silicon lesser will be the ductile-brittle transition temperature. Silicon has to be monitored within the range 2.4-2.8%.

Addition of manganese has positive as well as negative effects. Manganese improves the hardenability of ADI, but on the other hand it retards the austempering reaction due to formation of carbides during solidification. The segregation of manganese at cell boundaries could produce shrinkage, carbides and unstable austenite. The mechanical properties and the machinability of ADI will reduce due to these micro-structural defects and in homogeneities. The percentage of manganese in ADI should be restricted to less than 0.3% to attain improved mechanical properties.

The copper content of almost 0.8% can be added to improve the hardenability of ADI. Copper enhances ductility at austempering temperatures below 350 °C, but does not affect the tensile properties.

The hardenability of ADI can be improved by adding around 2% of nickel. Nickel slightly decreases the tensile strength but it improves fracture toughness and ductility below a particular austempering temperature.

Molybdenum is an important hardenability agent in ADI. The tensile and the ductile strength of ADI will decrease if the amount of molybdenum is above the limit required for hardenability. [83]

4.7.2.2 Manufacturing of ADI

ADI is manufactured by an isothermal heat treatment process known as austempering. Different grades of ADI are attained by different alloying and different austempering cycles respectively. Lower grades of ADI can be machined after austempering whereas higher grades of ADI have to be machined before the austempering process. Manufacturing of ADI components (gears) is done in the following way:

- The component is casted first as near to net shape as possible. The result is a ductile iron cast of the component (with additional alloying). The quality of the cast is very important and must have no compromises such as internal defects etc. Hence quality foundry techniques and operations are required.
- Major machining operations are carried out on the component before heat treatment when it is in a softer condition, which is easier to machine in this form thereby increasing tool life and lead time.
- Austemper the component till the required austempering temperature for a period of time according to the required grade
- The part is rapidly quenched after casting to avoid formation of pearlite to an austempering temperature range. This temperature has to be maintained above the martensite start temperature.
- In order to produce a matrix of needle like (acicular) ferrite and austenite, austempering has to be performed at a desired temperature for a specific and sufficient period of time depending on the grade.
- Finishing operations are carried out on the component. Carbide tipped tools can be used for better machinability.
- Additional finishing (cold working) operations to improve the fatigue properties of the ADI component are carried out on the component, like controlled shot peening, fillet rolling etc. Shot peening and fillet rolling are carried out especially for gears in order to reduce the residual stress generated.

Austenitizing can be performed using a high temperature atmosphere furnace. Another alternative for austenizing is the salt bath. Methods like flame or induction heating can be utilized for special cases. The austempering is mostly carried out in a nitrate salt bath or in hot oil up to 243 °C.

Machining of ADI grade 1 and 2 (see chapter 0) are easier than steels for a given hardness due to the presence of graphite. Graphite is easier to machine. Higher grades of ADI have to be machined before austempering. [34] [84]

4.7.2.3 Material properties of ADI

Tensile properties

The tensile strength of an ADI component is highly dependent on the austempering temperature as shown in Figure 4.11. Depending on the requirement of the component or the gear, austempering is carried out accordingly.

At low austenitic temperature (235-330 °C) the material consists of an acicular or needle-like ferritic phase containing very fine carbides. These have a lower-bainite matrix structure and have a high hardness (up to 500 HV) and can be very strong with tensile strengths in the range 1200 to 1600 N/mm^2, but have only limited ductility.

At high austempering temperatures (370-450 °C) the material consists of a coarser, feathery, carbide-free ferrite distributed in a high-carbon retained austenite. These austempered ductile irons produce an upper-bainitic matrix structure which has a lower hardness (280- 320 HB) and with tensile strengths in the range 850-1050 N/mm^2, and considerably higher ductility. [34]

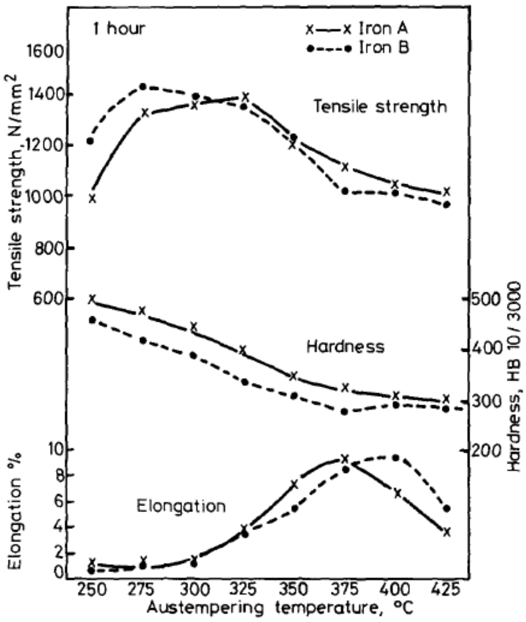


Figure 4.11: Effects of austempering temperature on tensile properties of two irons with different composition [34]

Fracture toughness

Fracture toughness is an internal resistance for a material to propagation of crack in the material. The fracture toughness of ADI is highly dependent on its microstructure and the toughness increases with increase in austenizing temperature. The toughness of ADI is very dependent on the amount of manganese used, toughness decreases with increase in the amounts of the manganese alloy in the required ADI composition. There are not may tests conducted on many grades of ADI hence the results are only estimated. ADI, considering its strength and grade has a high fracture toughness compared to conventional ductile iron and either equivalent or superior to cast and forged steel. [34]

Fatigue properties

The fatigue strength of ADI is competitive or superior to that of forged steels. The fatigue strength of ADI is improved significantly by gear rolling or shot peening or by machining after heat treatment.

Shot peening is a cold working process to improve the fatigue properties of the component. It induces a compressive stress layer and modifies the mechanical properties of metals. The surface of the metal is impacted with round metallic, glass, or ceramic shots with force sufficient to create plastic deformation. It is similar to sandblasting, except that it operates by the mechanism of plasticity rather than abrasion. This process involves removal of less material and also production of less dust. A pictorial description of shot peening operation can be seen from Figure 4.12. The effects and advantage of shot peening on the ADI gear teeth can be observed from Figure 4.13.

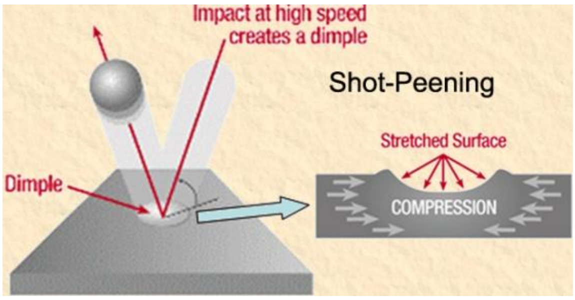
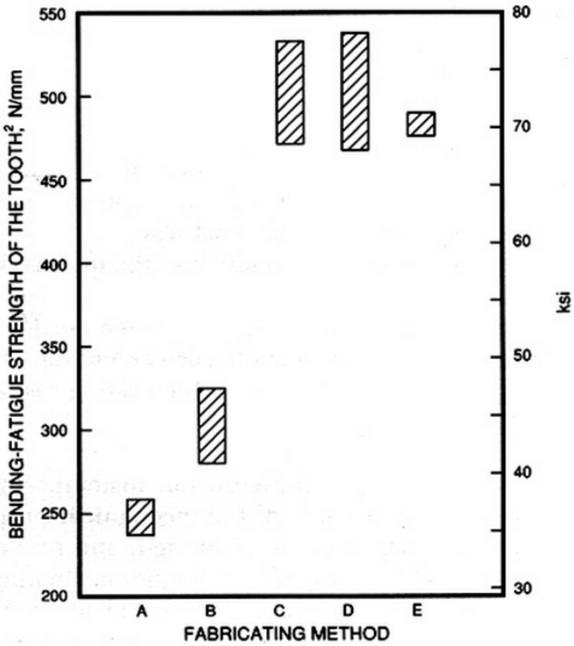


Figure 4.12: Shot peening [85]



A) Heat treatment after hobbing.
B) Hobbing after heat treatment.
C) Shot-peening, 0-35 mm Almen A.
D) Shot-peening, 0-45 mm Almen A.
E) Shot-peening, 0-55 mm Almen A.

Figure 4.13: Effect of hobbing and shot peening after heat treatment on the bending fatigue strength of ADI gear teeth [84]

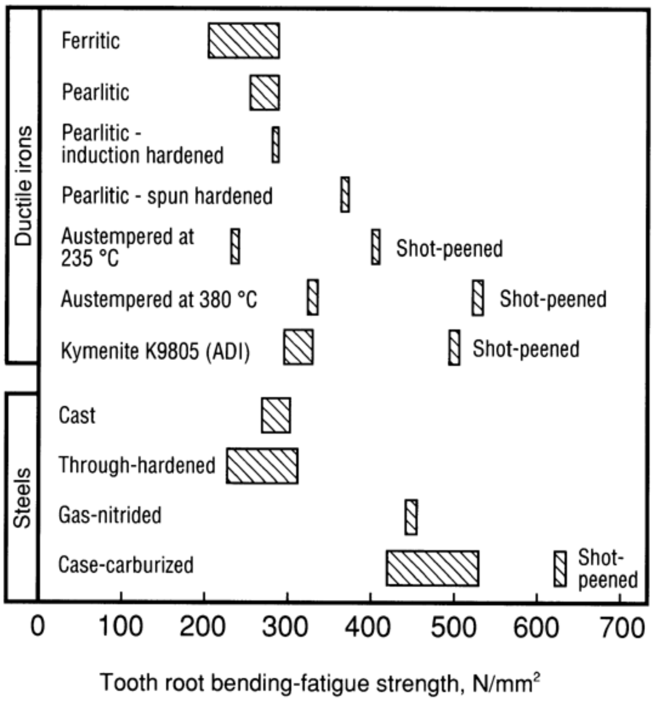


Figure 4.14: Comparison of bending-fatigue strength of ADI with conventional Ductile Iron and steels used for gear applications [84]

It is observed from Figure 4.14 that shot peened ADI has tooth root bending fatigue strength better than casted and heat treated ductile Irons, and cast and through hardened steels. Moreover, it is also noted that shot peened ADI is a good competitor to case carburized and gas nitrided steels.

The strain induced transformations increase the localized volume and induces high compressive stresses in the transformed areas. In addition to this a significant increase in flow stress and hardness is also achieved. Crack formation and growth is inhibited by the compressive stresses. The compressive stresses also improve the properties of ADI significantly. [34] [84]

Abrasion and wear resistance

ADI offers superior abrasion resistance compared to its competitive materials over a wide hardness range. The strain generated transformation of stabilized austenite originating on the surface of the ADI component, when it is deformed, contributes to improved abrasion resistance and reduced sensitivity of abrasion resistance to hardness.

Figure 4.15 illustrates that relative abrasion resistance is higher for austempered irons and increase with hardness for any material. The abrasion resistance can be optimized accordingly by varying the austempering process according to the requirement.

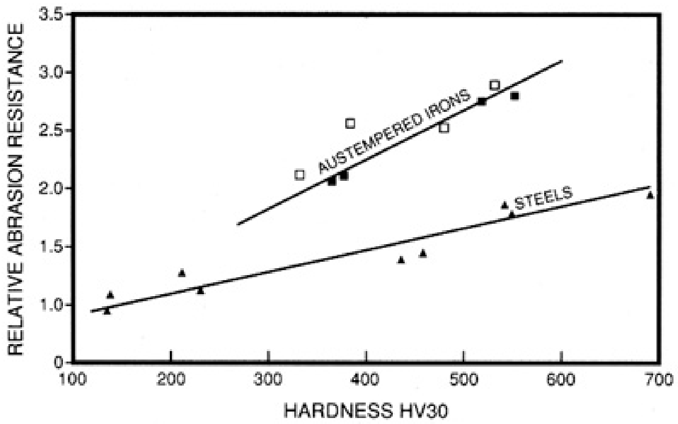


Figure 4.15: Comparison of the relative abrasion resistance of ADI with those of different abrasion resistant steels [33]

Figure 4.16 illustrates that ADI has improved abrasion resistance when compared to quench and tempered ductile iron and steels . ADI experiences less volume loss at similar hardness levels, resulting in a component with improved wear characteristics.

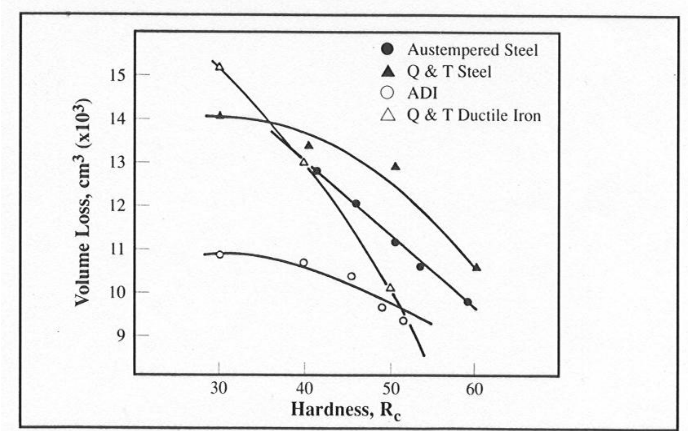


Figure 4.16: Pin Abrasion Test, Comparing Volume Loss at Equivalent Hardnesses [33]

ADI has excellent wear resistance property due to the carbon enriched austenite present in its matrix. When exposed to high normal forces the austenite undergoes strain induced transformation which is the main reason for ADI’s excellent wear resistance. Austenite can undergo strain induced transformation owing to its thermodynamic stability.

Good wear resistance in any material is generally obtained by ensuring as high hardness as possible. Low austempering temperatures (235-250 °C) produce ADI of high hardness (480-550 HB) and good wear resistance. As the austempering temperature is increased, the hardness and hence the wear resistance progressively decreases. [84]

Damping properties

Damping capacity is the property of a material to absorb energy from vibrations due to some form of internal friction. ADI has superior damping properties due to the presence of graphite nodules in the ausferrite matrix. Due to ADI's superior damping properties the internal vibrations are reduced/ eliminated hence reducing the noise drastically from gears. [33]

Table 4.1: Relative comparison of noise reduction characteristics [96]

Vibration and noise reduction	
Type of metal	**Relative decrease in amplitude vibration/cycle**
Steel	1.0-2.0
Cast gray iron	20-60
Heat treated gray iron	20-30
Cast ductile iron	3.0-9.4
Q & T Ductile	3.0 -5
Austempered ductile iron	10-15

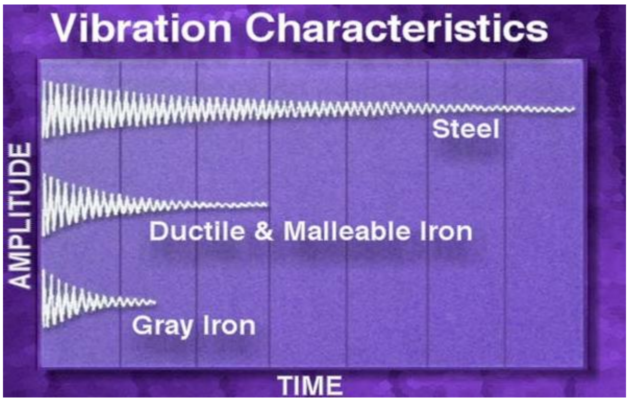


Figure 4.17: Relative comparison of vibration characteristics of ductile and gray iron with steel [33]

4.7.2.4 Available grades of ADI

The grades of ADI to be used depend on the application and requirements. The grade 5 ADI is the most suitable for use in timing gears for heavy duty applications [33], lighter grades may be sufficient for medium and light duty applications (see table 4.2).

Table 4.2: ASTM A897 Grades of ADI [33]

Former Grade Designation	Tensile Strength (MPa / Ksi)	Yield Strength (MPa / Ksi)	Elongation (%)	Impact Energy (Joules / lb.-ft.)	Typical Hardness (BHN)
-	750 / 110	500 / 70	11	110 / 80	241-302
1	900 / 130	650 / 90	9	100 / 75	269 – 341
2	1050 / 150	750 / 110	7	80 / 60	302 – 375
3	1200 / 175	850 / 125	4	60 / 45	341 – 444
4	1400 / 200	1100 / 155	2	35 / 25	388 – 477
5	1600 / 230	1300 / 185	1	20 / 15	402 - 512

4.7.3 Powder Metallurgy

Powder Metallurgy (PM) is a widely used and developed method of manufacturing reliable parts. The PM industry has an annual turnover of more than six billion Euros, in Europe only [86]. The PM technology has been successfully used in many different industries. Owing to the economical benefits of using this technology the market has grown from 0% in 1986 to 50% in 1997 of parts used in the aircraft industry [6]. Industrial experts have also forecasted that the PM industry will be steadily growing in many areas of the automotive industry.

Recent advancements in this field show that PM is indeed a good option for producing parts that requires high precision, strength and durability at economical prices in high volumes and is a process that has become competitive to other metal forming technologies. The PM process allows the manufacturers to produce net or near net shaped products. Excellent dimensional precision will help reduce costs, since machining can be more or less excluded from the manufacturing process. Observed features with using the PM manufacturing process are: [86]:

- Complex shapes
- Controlled porosity
- Controlled performance
- Good performance in stress
- Absorption of vibrations
- Special properties such as hardness and wear resistance
- Precision and surface finish
- Narrow tolerances in large series
- Good alloying possibilities
- Good machinability

References: [5, 7, 35]

4.7.3.1 Powder metallurgy manufacturing process

In this chapter the essential parts of the PM manufacturing process will be explained. The different processes of the PM manufacturing process will be explained in this chapter.

The powder metallurgy technology allows the industries to apply an almost endless range of alloy combinations. This is one of the great advantages of this technology. Commonly used metal powders are: [87]

- Stainless steel
- High-strength and High-alloy steels
- Aluminium and aluminium alloys
- Iron
- Copper
- Brass
- Bronze
- Nickel silver

The powder metallurgy manufacturing process can be divided into four main steps (see Figure 4.18), where the fourth one may be optional:

- Mixing
- Compacting
- Sintering
- (Various final treatments)

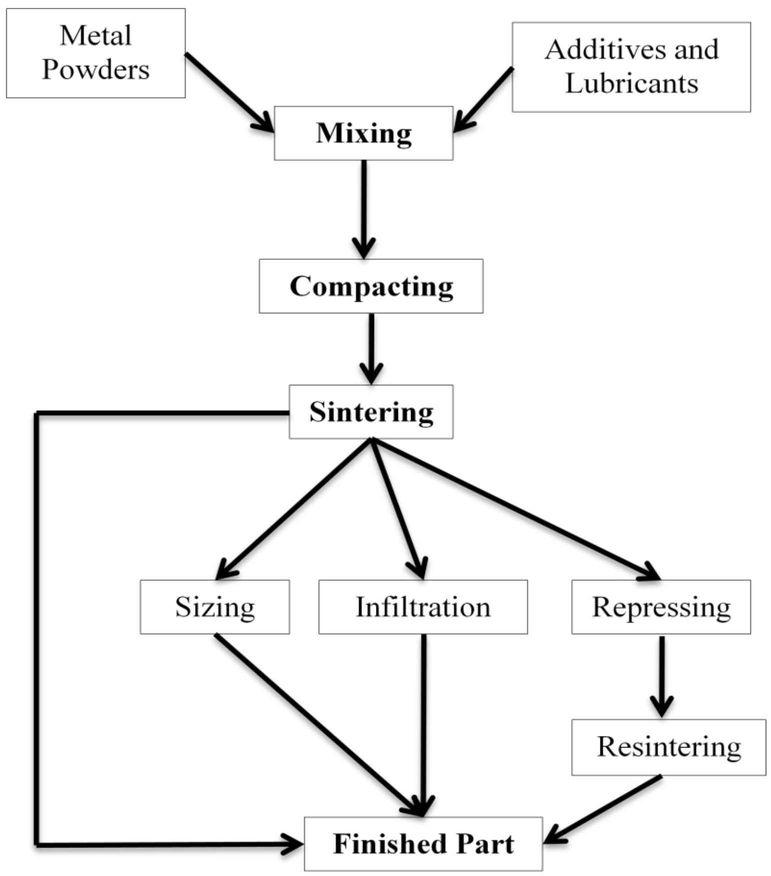


Figure 4.18: Simplified fabrication pattern of the PM process

References: [5, 6, 7]

Mixing/Blending
The PM process is initiated by making a careful and correct choice of powders. A mixture of various grades and grain sizes, or powders with different compositions is used. Solid lubricants and other additives suitable for the application are added. The lubricants are used to improve the flow characteristics, compressibility and to reduce pressure gradients by reducing friction between powders and compaction tools. This also reduces the wear and increases life of the die. Specific demands are put on the mixers that are used to achieve the best results. The main aim of the mixing process is to achieve a uniform mixture of the powder while controlling the density of the mix to get a good flow of the powders for filling the dies. [5] [7]

Compaction (Forming process)
After mixing the powder mixture is compacted using mechanical, hydraulic or hybrid presses and rigid tools. They are used to produce the desired shape, close to final dimensions, level and type of porosity as well as obtaining the strength required for the following handling of the green compact (e.g. die ejection and transport to sintering furnace). Compaction can be executed by using several different techniques. The compaction procedure can be made in room temperature as well as in elevated temperatures. The shape and properties of the final product controls the compaction method used. For achieving the desired properties from a PM part a variety of processing techniques have been developed. Except for the commonly used press-sinter method the following are also some methods used:

- Hot pressing
- Isostatic pressing
- Powder rolling
- Powder extrusion
- Powder forging
- Hot isostatic pressing (HIP)
- Injection molding
- Warm compaction
- High velocity compaction

However only the following consolidation techniques will be investigated more closely in this chapter:

- Hot and cold die pressing
- Hot and cold isostatic pressing
- Warm compaction

References: [6, 7, 35, 88]

Cold die pressing

Die pressing (also called die compaction or uniaxial pressing/compaction) is the most commonly used method. The compaction process is made in four steps; filling, pressing, withdrawal of the upper punch and finally ejection of the part (see Figure 4.19). The die is gravity-fed with the powder mix by a feeder shoe. The compaction can be done either by one or both of the punches. The pressing is thereby divided into two categories; single action pressing and double action pressing. In single action pressing the upper punch is pressing the powder, whereas the lower press is stationary. The part is lifted from the die with the lower punch. The feeder then fulfills the function of moving the finished part away from the pressing tool and at the same time fills the die with powder, and the process is then repeated.

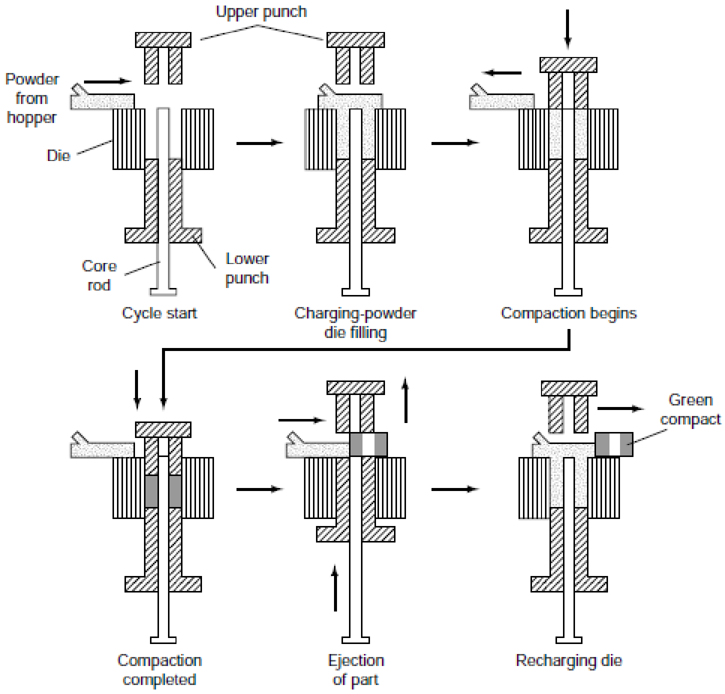


Figure 4.19: Compaction cycle, single-action compaction [6]

The powder is pressed in dies made of rigid steel or carbide. The pressures used are dependent on the density required and is typically in an order of 150 to 900 MPa, which creates densities up to 90% of full density. The pressure will not be uniform throughout the part due to friction that arises between the powder and the die wall, as well as between the particles in the powder. A nonuniform density is thereby produced which will be exacerbated by increased part dimensions. As mentioned earlier the mechanical properties of the parts are related to the uniformity and the level of density of the green (as-pressed) part. However by using a double-action compaction method, the pressure distribution can be improved. The powder is then pressed from two directions, the top and the bottom of the part, simultaneously.

The density that can be obtained in a certain press is limited by the tensile strength of the tool steel. The compaction pressure needed to acquire higher densities, or the pressure needed for parts above certain dimensions while maintaining the density, will make this process uneconomical. Larger presses and stronger tools are required to cope with increased pressures and thereby give higher tooling costs as a consequence.

References: [6, 7, 88]

Cold isostatic pressing
Pascal's principle states that a fluid will increase the pressure at all points by the same amount by the increase of pressure in one point in a completely enclosed container. Thereby in the process of isostatic pressing the powder metal is contained in a flexible mold that is subjected to isostatic pressure, i.e. equal pressure from all directions from a pressurized surrounding liquid.

In cold isostatic pressing water or oil is used as the pressuring medium. Pressures up to 800 [MPa] can be reached with this technique. The benefit of this is that by the applying an isostatic pressure the part will have a uniform density and increase with about 5-15% compared to the cold die compaction thus giving the possibility to create larger parts. This also means that the powder can be compacted without the use of binding or lubricant additives. The downsides with this process are; less precise dimensional control compared to die compacting, rougher surfaces and lower rate of production.

References: [6, 7, 8, 88]

Hot die pressing
Hot die pressing (also called pressure sintering) is a part of the hot consolidation methods to produce fully dense powder metals with high mechanical properties. The increased temperature of the metal powder makes many metals softer and gives the possibility to achieve higher densities. By combining the sintering process with the compaction process it is possible to reach higher densities compared to the normal cold compaction process. The resistance of plastic deformation in metal particles is reduced with elevated temperature. Hence, less pressure and less energy is required for compaction as well as allowing higher densities to be reached. Factors like; shape, size and size distribution of the powder grains have high influence on the efficiency of cold pressing but less effect on hot pressing.

Temperatures up to 2200 °C and pressures reaching 160 MPa is usual for hot pressing, but varies with the die materials and the powder metals that are to be compressed. Hot pressing can be made through six main steps:

- The mould is filled with powder, or a compacted pre-form is placed in the mould
- The mould is heated to a predefined temperature
- Pressure is applied to the die cavity
- Pressure and temperature is increased during compaction
- The pressure and temperature is maintained for a certain amount of time
- The mould is cooled under pressure

Some metals require inert atmosphere (non-reactive gases are used and no or very little oxygen present) or vacuum due to high reactivity with the surrounding gas due to the risk of oxidation during the last step of slow cooling. The dies used in this process are mostly made out of graphite due to its mechanical properties at high temperatures and the availability of grade variations. The strength of graphite increases with temperature and has a relatively low coefficient of thermal expansion.

The downsides of the hot pressing procedure are the limitations of producing large components with high length-to-diameter ratios and complex shapes.

References: [6, 7, 88]

Hot isostatic pressing

One of the most interesting PM production processes is hot isostatic pressing (HIP). It was invented by the Battelle Institute in USA, in the 1950s. This process is another way of combining the sintering process with the compaction process to be able to produce parts with up to 100% of theoretical density. HIP gives the possibility to produce PM parts with high and isotropic mechanical properties with uniform density and can combine the compaction process with the sintering process. HIP is typically used as a complementary to the more conventional processes where high densities cannot be achieved.

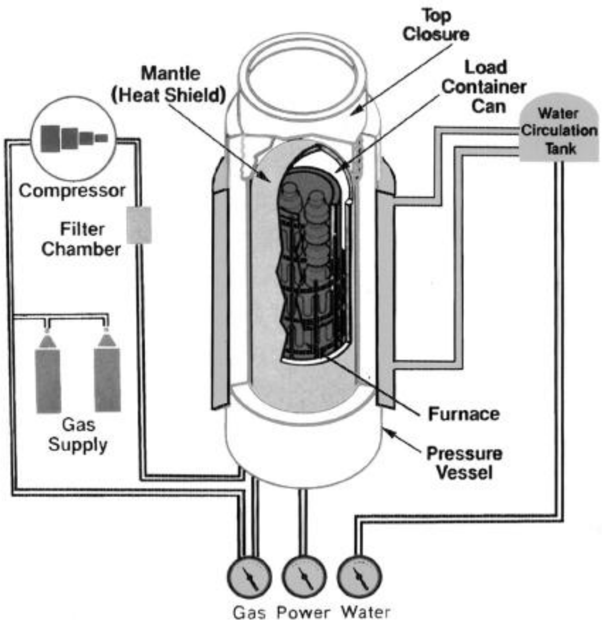


Figure 4.20: Hot isostatic pressing tools [36]

The difference between this method and the cold isostatic pressing procedure is that the pressure is built up using inert gas (usually Nitrogen or Argon) instead of liquid. Pressures up to around 300 MPa and temperatures reaching 3000 °C can be used, but varies depending on the material. The temperature should be kept below the melting point of the material. The part is kept under pressure and elevated temperature in a furnace for a certain amount of time and then slowly cooled and depressurized.

The HIP system usually consists of the following parts (also see Figure 4.20):

- Pressure vessel
- Furnace
- Gas storage
- Gas handling system
- Control system
- Auxiliary Systems

The cost of such a system could be relatively high. It is also shown that the cost of the equipment steadily increases with the size of the component that is to be produced due to higher pressures and temperatures necessary to achieve the right component mechanical properties. These are a few factors that affect the tooling costs and apply for other pressing techniques as well. To reduce the cost of the HIP process more economical alternative approaches like the Ceracon process, rapid omnidirectional compaction process and the STAMP process.

References: [6, 7, 8, 36, 88]

Warm compaction

Warm compaction replaces the normal compaction process in the manufacturing of PM parts. It is developed with the aim to reach higher density by increasing the temperature of the powder. This technique will allow an increase in density without the need of expensive secondary treatments like double pressing and double sintering. Conventional cold compacting processes reach densities less than 7.1 g/cm^3 which has mechanical properties that are significantly lower than those of a fully densified or wrought steel equivalent. By using warm compaction it is possible to produce densities (around 7.5 g/cm^3) close to those made by double pressing and double sintering processes and thereby increase the overall performance of the PM component.

The warm compaction process use temperatures above room temperature but below the hot-forging range, usually around 75 °C to 150 °C. The elevated temperature gives larger plastical deformations due to that the particle yield strength will decrease. However according to [37] there should be other dominant densification mechanisms involved. This would be the rearrangement of particles that takes place. In combination with the lubricants added to reduce the friction between particles and thus allow for higher densities to be achieved with the same pressure applied.

It has been shown that the compaction pressure is the most important factor when it comes to the green density of warm compacted parts. It was in [38] compared to two other factors; the condition of the lubricant used and the compaction temperature.

References: [6, 7, 37, 88]

Sintering

The green shape produced from the compaction goes through the sintering process as a last stage of the PM manufacturing. The green part which has very low mechanical properties needs to be heated to achieve the true properties. The part is heated to a temperature below the melting point of the material and most commonly without an external pressure. As mentioned earlier, the sintering process can be combined with the compaction process where external pressure is applied to reach high densities. This will create metallurgical bonds between the powder particles by solid state diffusion (atomic motion at the sintering temperature). This introduces much higher mechanical strength to the form and is the whole purpose of the sintering process.

The sintering conditions as well as the sintering properties will vary considerably depending on the compaction process used. The sintering can be performed with different variables and techniques that affect the microstructure and properties of the sintered part. These can be divided into material dependent and process dependent variables. The variables affected by the material include the chemical composition, size distribution and degree of agglomeration of the powder, green density etc. The homogeneity of the powder mixture is important, especially in a mixture of more than one material, to attain a powder of high compressibility and sinterability. The process dependent variables include thermodynamically related factors, namely; temperature, time, atmosphere, pressure as well as heating- and cooling rate.

The reduction in surface free energy of the particles is the driving force for the sintering process. It is via densification and grain growth that the reduction in total interfacial energy is happening and is the basic phenomenon of sintering.

Solid phase sintering and liquid phase sintering are two ways of which the sintering process can be accomplished. In solid state sintering the green compact is densified in a solid state, with no liquid phase present and heated to temperatures around 50% to 80% of the melting temperature. Solid phase sintering can be divided into three primary stages; neck formation, neck growth and evaporation-condensation, respectively. Neck formation is occurring by surface and grain-boundary diffusion between particles (see Figure 4.21). In the second stage the necking between the particles is increased and involves mass transfer which is dependent on the composition of the material, sintering conditions and the sintering step. In the final step the grains are rounded by evaporation of the material and may result in not only densification but also unwanted shrinkage.

Figure 4.21:Densification of powder particles

The liquid phase sintering method is the most widely used form in the industry, even though the solid phase sintering method is the most understood. The liquid phase sintering method usually increases the rate of grain growth as the bonds between particles become more rapid with higher temperature, longer sintering time or smaller particles. Smaller particles means smaller diffusion distances and larger curvature stresses which results in faster sintering. A liquid phase of the material is present with a solid state simultaneously. The densification is caused by a capillary force between the liquid and the grains that pulls grains together with the aid of the increased temperature that softens the material.

Shrinkage of the part is a problem that might occur in the sintering process due to green density variations. The density variation might cause extensive shape differences. Therefore the homogeneity of the densification in the compaction process plays a great role for the prediction of the final shape of the part. The part with high length-to-diameter ratio stands a higher risk of being misshaped during sintering. Numerous ways of compensating and avoiding this phenomenon has been developed.

References: [6, 7, 9, 10, 11, 39, 88]

Secondary treatments
By applying post-sintering secondary operations the mechanical properties of the PM part can be enhanced. This is especially useful for high loaded applications where the physical and mechanical properties of an untreated part are not sufficient. There are numerous ways of reaching these properties, e.g. by using a densifying treatment to eliminate the disadvantages of a porous PM part or by using well understood and widely used heat treatments.

Thermal treatments
As stated earlier the density of a PM part affects many of its mechanical properties. This is also the fact when it comes to the hardenability. One of the major positive aspects of PM is to produce near net shape parts where little machining is necessary. Thus as tempering and quenching can result in shrinkage of a PM part, the hardening process becomes very critical compared to the wrought steel manufacturing where machining usually is applied after hardening.

Basically all advantages from heat treating wrought steel parts can be achieved with PM when conducted in a proper manner. Thus the porosity has to be kept in mind and the effects it has on the hardening process. The thermal conductivity is a determining factor when it comes to heat treatments. The thermal conductivity is in turn much dependent, amongst other factors, on the density of the PM part. Wrought material and PM parts with high densities have high thermal conductivity giving short heating and cooling periods. For tempering methods up to double the soaking time is needed compared to wrought materials due to the difference in density. Thereby for parts with low density and with big open surfaces the case depth will be nonuniform. [12]

Selective densification
The residual porosity after a normal sintering process is one reason for conventionally manufactured PM components to have limited mechanical properties in comparison with wrought steel. In this chapter some of the possibilities of increasing the mechanical properties of the PM material through selective surface densification methods will be explained in the chapters to follow.

Surface densification
One way of improving static and dynamic properties of PM gears and to make them more useful in high stressed applications like automotive power transmitting parts is by using surface densification. This technology allows for full densification of the surface but with standard porosity levels in the core. The increased density is desirable for attaining the same surface durability and bending fatigue performance as that of wrought steels. To achieve full density parts specific PM processes are required (HIP, Powder forging) and are relatively expensive. To eliminate the need for such high cost manufacturing processes there is a need for processes that increases the mechanical properties of PM parts produced with more conventional and economical methods.

The upper limits for PM gears are mostly defined by the overall gear size, low production volumes and, most importantly in this case, by the required compaction pressures for creating full density at a required depth. Tests conducted by Höganäs and Scania shows that the surface densified gear showed an increase in fatigue performance compared to a solid steel gear (SS 92506) which was used as a reference material [40]. The increase in mechanical properties was partly due to the higher levels of compressive stresses in the surface of the surface densified material. It is desired to have compressive stresses at the surface. This increases the fatigue resistance of the surface, whereas tensile stresses introduce higher stress levels at the surface during loading, resulting in an opposite effect.

Figure 4.22 shows the result from the surface densification process, where the densification can clearly be seen in the surface of the tooth. The results from a hardness measurement showed that the surface hardness of the surface densified PM gear had the same or a higher hardness than that of a reference solid steel gear. Removing the pores in the surface of the material and achieving high density at the surface of the teeth is shown to be crucial due to that the highest stress concentrations on a gear tooth is acting on the surface region. It is however vital to ensure that the stresses are mainly acting within the thickness of the densified area. [40]

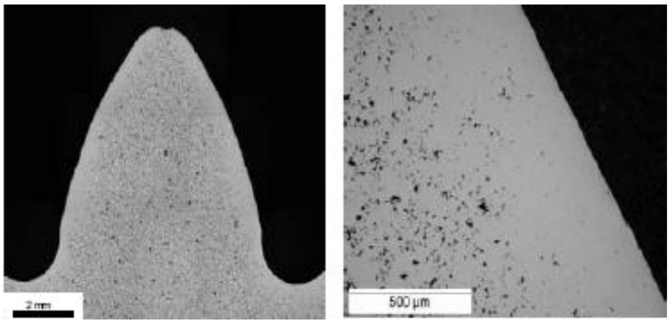


Figure 4.22:Surface densified gear tooth [40]

Gear rolling
Geometry and fatigue life has an increased importance when choosing material for gears. Certain production processes will allow for fully dense PM parts, but with increased cost. Increasing density of the gear tooth surface is desired to achieve the right mechanical properties, but with the core density maintained. One way of producing a densified surface is by using a method called gear rolling. The densification of the gear surface will not only increase mechanical properties but also increases physical properties, e.g. improved gear tooth geometry and surface finish. Other benefits with the gear rolling process are (from a manufacturing point of view); short manufacturing times, suitable for automation and has long tool life.

The gear to be treated, which is pressed and sintered with an overmeasure, is placed between the tools and pressure is applied radially as described in Figure 4.23. By making the gear over dimensioned after the compaction and sintering process the dimensional change during the rolling process is taken into account. The pressure introduces compressive stresses in the tooth surface as well as increasing the density, and stops when the desired dimensions are reached. To achieve a homogeneous densification of the gear, the rolling direction will altered during the rolling process. After the rolling process the material will have an amount of spring back due to elasticity in the material and has to be considered in the design. The increase in surface density allows for higher loads and increases the fatigue life of the gear which is vital in highly stressed heavy duty applications.

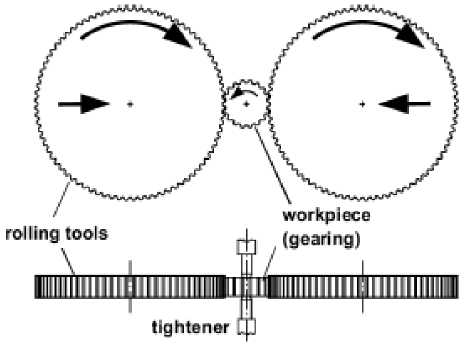


Figure 4.23:Gear rolling principle [42]

References: [5, 41, 42, 43, 44]

Shot peening

As mentioned previously in chapter 4.7.2.3, shot peening is another method for increasing mechanical properties on the surface of gear teeth. This process allows the option of treating more specific areas that needs densification. In wrought materials the shot peening process will introduce compressive stresses and hence increase load bearing capacity, fatigue and wear resistance. However, there is a difference in the response to shot peening in wrought and PM materials. Residual stresses due to compression occur in the PM material as well, but are density dependent. High density (> 7.4 g/m^3) PM parts respond better to the increased residual stresses in comparison with lower densities where the porous structure increases the risk of crack initiation. Similar to the gear rolling process, shot peening is used on post-sintered PM gears to remove the excess porosity in the surface region, hence increasing mechanical properties (see chapter 4.7.3.2 – Density).

References: [40, 45, 46]

4.7.3.2 Mechanical properties of PM manufactured parts

The mechanical properties of PM parts are dependent on a number of factors, each of which should be considered carefully to achieve the desired properties of the final part:

- Chemical composition of the powder (e.g. alloying)
- Particle properties
- Density
- Processing techniques (sintering and heat treating conditions)

From the previous manufacturing chapters it is obvious that these factors are correlated and can be extended further. As an example the density is highly dependent on the processing techniques which in turn are dependent on the tools, pressures and temperatures that affects the micro structure and hence the mechanical properties of the material.

Due to the vast possibilities of variation in the manufacturing processes and metal alloying that the PM technology offers, the mechanical properties will vary to a large extent.

References: [7, 13, 14, 89, 87]

Density

The density is by far the most important factor controlling the mechanical and physical properties of PM parts. The most important properties affected by the density are:

- Modulus of elasticity
- Poisson's ratio
- Thermal conductivity (and thereby hardenability)
- Hardness
- Fracture toughness
- Tensile strength
- Yield strength
- Fatigue strength
- Impact strength
- Ductility
- Surface roughness
- Internal damping

The Young's modulus, Poisson's ratio and fatigue properties increases with increased density (see Table 4.3). Furthermore, the fracture-limited properties of toughness, ductility and fatigue life are more sensitive to density variations than strength and hardness.

Table 4.3: Relationship between Young's modulus, E, and density for PM materials [89]

Density	g/cm³	6.6	6.8	7.0	7.2	7.4	7.86
Young's Modulus	GPa	114	126	140	154	169	206

It is due to the pores in the material that the mechanical properties are abated with a less dense microstructure. Even though a residual porosity of less than 5% can be reached, even small amounts of porosity in the part will lower the mechanical properties of a significant amount. The increased porosity decreases the load bearing cross section in the material and is one of the reasons for the abated mechanical properties. The notch effect is another reason for the decrease in mechanical properties. This is a result of the stress concentrations created in the material due to variations in the microstructure (porosity). Porosity is defined as the ratio of the current density and the actual material density as follows*;*

$$\mathrm{P} = 1 - \rho^{*}/\rho_{s} \qquad (4.5)$$

Where ρ^{*} is the density of the porous PM material and $\rho_{s}$is the full density of the metal of which it is made of.

Reference: [7, 14, 47, 89]

Tensile strength

The tensile strength is often used for design purposes as a reference and is a property used for characterizing the mechanical properties of materials. Figure 4.24: Tensile and Yield strength vs. Density shows a steady increase in ultimate tensile strength due to the increase in density. The values presented are only showed for a reference and will vary for different grades and manufacturing procedures. However, as mentioned earlier the porosity of the material has a more notable effect on ductility than the strength.

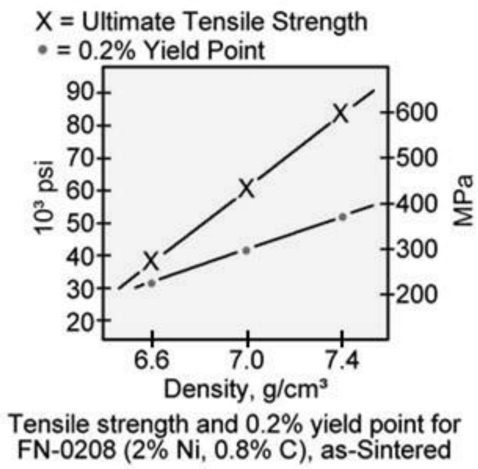


Figure 4.24: Tensile and Yield strength vs. Density [87]

References: [7, 47, 87, 89]

Ductility

Figure 4.25 shows the ductility of PM materials, which is further affected by the porosity in the microstructure and is relatively low comparing to wrought equivalents. By further increasing the density of the material, e.g. by using re-sintering techniques, a significant increase in ductility will be achieved. In comparison with the much more steady increase in tensile strength as in Figure 4.26, the ductility is highly reduced due to a small percent increase in porosity. The pores introduce a crack initiation mechanism which acts like stress raisers and is the reason for the drastic change in ductility. Furthermore, the shape, spacing and size of the pores also play a vital role. Unlike wrought materials the spacing between pores in PM materials is close and is the material is thereby much more sensitive to these factors. [47]

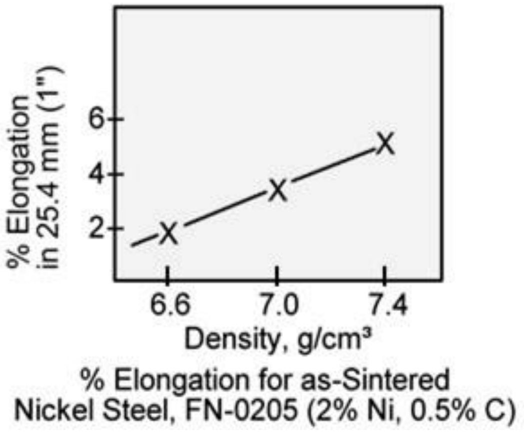


Figure 4.25: Elongation vs. density [87]

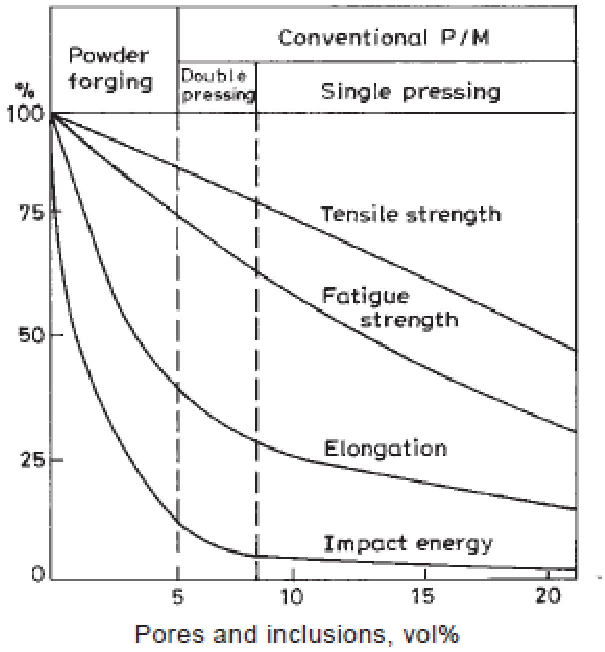


Figure 4.26: Mechanical properties in percent of values at full density [7]

Hardness

The hardness value is a measurement of the materials resistance to plastic deformation. Thereby, PM materials cannot be directly compared to those of the wrought equivalents. The hardness value measured on PM materials is referred to as either "apparent hardness" or "particle hardness". The apparent hardness value measurement is made on the solid material and the porosity. It gives a lower value compared to the particle hardness which gives the actual hardness value and can be used to get a measurement of the wear resistance of the material. An obvious conclusion is that since the apparent value includes the porosity of the material, the hardness value will increase with increased density.

References: [7, 47]

Impact strength
Impact strength is a measurement of the amount of energy absorbed by a material before fracture. Seen in Figure 4.27 is that the amount of absorbed energy is strongly dependent on the density and the powder composition. At higher densities the dynamic properties of PM materials are to a large extent dependent on the micro structure (pore size, shape and spacing) as well as the particle boundaries. The pores act like stress raisers and has a negative effect on the amount of energy possibly to be absorbed by the material.

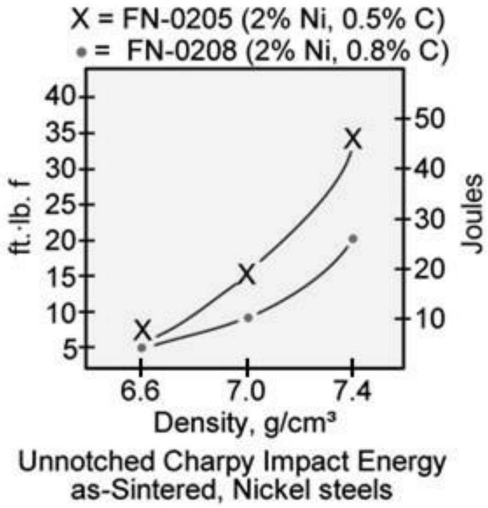


Figure 4.27: Charpy impact energy vs. density [87]

References: [15, 87]

Fatigue strength
Similar to the impact strength, the density, or more precisely the amount of pores present, affects the fatigue strength of the material. Numerous studies have been conducted that can depict the strong linkage between fatigue properties of PM materials to the density. As mentioned earlier the crack initiation around the pores is one of the main mechanisms for fatigue failure. Strain hardening due to stress concentrations around the pores caused by relatively low strain levels. The plastic zones created by this result in a quick growth of the crack. In comparison to wrought materials, where the less pores and impurities are present, the porous PM structure experiences a much more inhomogeneous stress distribution. The crack propagation is further affected by the interaction between the crack and the pores due to the release of stress concentration when the crack reaches the pores. It will continue to grow when there is sufficient stress concentration on the other side of the pore. Furthermore, the pore structure and the purity of the microstructure enhance the dynamical properties further. Fine and rounded pores are most beneficial for dynamic properties. [15]

Damping properties
From a mechanical property point of view, the porosity of PM materials is in every way a negative factor that has to be eliminated for heavy loaded applications where good mechanical properties are vital. A vast amount of studies and the recent development in the PM field has thus been concentrated on finding efficient ways of eliminating the density/strength problem. However, one positive aspect of a porous structure is the increase in internal damping.

The damping capability of a material is measured by the energy that is dissipated in the material during mechanical vibration under cyclic loading. The damping behavior of PM materials is linked to the pores in the material structure. These act as the vibration damping mechanism through micro-plastic deformation caused by stress concentrations around the pores. The vibration energy is by internal friction dissipated as heat out of the system. The amount of energy dissipated in the system can be measured by the reverberation time. Measuring the reverberation time of materials is a way of attaining the damping properties. It is a measurement of the time it takes for the sound level of a certain excitation to reduce by 60 dB (see: [48] and [49])

References: [16, 50, 51, 52, 53]

4.7.3.3 PM modeling and simulation methods

PM manufacturing process

Attempts of modeling parts of the PM manufacturing process can be found in literature. Research has been done in this field in order to predict the outcome of a certain process through numerical modeling. This, as an example, can help to optimize the tooling to prevent density gradients. Considering that applicability of these simulations is mostly utilized by PM manufacturers rather than for example gear designers, this topic will not be further examined. For deeper knowledge regarding the modeling of the PM production process see the following papers and book [17], [54] and [55].

PM gears

The complexity of the microstructure and variations in the mechanical properties of the PM technology requires specific considerations to be made regarding the modeling and simulations of parts made from this production process. In [56] it is stated that PM gears have not yet been fully developed in all aspects. Hence, the properties of these materials have not yet been incorporated into most tooth contact analysis softwares.

The software Zako3D, developed by WZL in RWTH Aachen University, is designed for making tooth contact analysis of gears taking the mechanical properties of the PM technology into consideration. An FE-model of a gear section is automatically created by using the geometric data inputs of the tooth flank. When the FE-model has been generated data is inserter, e.g. material properties. As the correct inputs have been made, the software makes contact analyses, of which, deformations, contact patterns and stresses on the gear teeth can be derived.

Modeling of PM gears may require the need of specifying a varying density throughout the structure. As an example a surface densified PM gear was designed in [56] for analyzing the micro geometry optimization of PM gears. The properties of the powder metal base material were defined for the gear. To model a surface densified gear the gear teeth is defined with a core density and a variation of densities up to the surface of the teeth (see Figure *4.28*). The density, module of elasticity and Poisons ratio is possible to define separately in each of these sections within this software. It was thus illustrated that this software is adapted to many of the deviating aspects in material properties of PM gears.

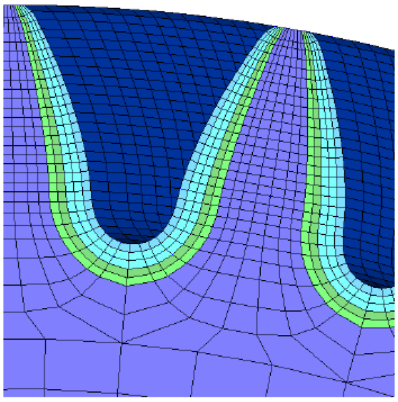


Figure 4.28*: FE-model of a PM gear section [56]*

4.7.4 Austempered Gray Iron (AGI)

Gray iron is an alloyed type of cast iron having graphitic microstructure. Gray iron is widely known for its light weight, wear resistance and good damping properties.

It is manufactured by austempering gray iron at a particular temperature and a particular time depending on the grade. It is austempered to improve its properties. AGI offers excellent damping capability, better than ADI and superior to steel due to the presence of graphite flakes in their ausferritic matrix unlike the presence of spherodical graphite in ADI. Moreover AGI offers excellent wear resistance and is lighter in weight. AGI has a lower cost than ADI and steel. AGI is not as strong when comparing bending fatigue and contact fatigue strengths of ADI and steel. Hence AGI can only be used for lighter loaded components. AGI could be used for some auxiliary components where the loading is minimal or within the handling range of AGI (e.g. oil pump). More research and investigations has to be conducted for using AGI for gears.

References: [33, 90]

4.7.5 Plastic gears

Plastics gears could be suitable for timing gears owing to its reduced noise, weight and cost. They are manufactured by injection moulding and then are hobbed and finished to precision. Plastic gears could be used but have several obvious limitations. Much more research is needed in order for plastics to sustain the fatigue and the high loading capabilities without deforming or failing, but plastic gears could be a good alternative in the future when it comes to the noise point of view. Plastic gears are very silent compared to steel gears. They also don't require a high grade of lubricant since plastics are self lubricated. If plastics can be used in the future it could be for gears experiencing lower fatigue levels. Tests have been conducted without combustion in order to compare the noise reduction potential of plastic gears. [57]

Some types of plastic materials available are; nylon 4.6 reinforced with carbon fibres, polyamide 6.6 reinforced with carbon fibres, phenolic plastic gears with metal hub for better heat convection.

4.7.5.1 Tests conducted using plastic engine timing gears

An experimental test was conducted by IVECO in which the steel timing gears were substituted by plastic gears to compare the noise emission with steel and plastic gears. Two of their timing gears were changed from steel to plastic. The experiment was conducted without actual combustion. [58]

The test was conducted on an inline six-cylinder IVECO 8460. The set up had four gears; one on the crankshaft, one for an idler and two similar gears for the camshaft and the injection pump. The camshaft and the injection pump gear were replaced with plastic gears. This was done in order to have a steel plastic meshing. The results showed that plastic gears reduced noise drastically about 5-6 dB at lower speeds and at a lower frequency and about 1-2 dB at high speeds.

4.7.5.2 Advantages and disadvantages of plastic gears

The advantages of plastic gears are listed below: [57]

- Lighter in weight
- Plastic gears allow a number of lubrication options. It is possible to eliminate external lubrication and take advantage of the materials natural lubrication properties resulting from resins like acetal and nylon. Some rigorous application may require lubricants like silicon and PTFE or even external grease can be applied
- Drastic reduction in noise
- Good chemical and shock resistance[

The disadvantages of plastic gears are listed below: [57]

- Strength
- Plastic materials will heat up three to five times more than metal due to its poor thermal conductivity
- higher the temperature more the elastic deformation which is not favorable for heavy duty fatigue loading as of now

4.7.5.3 Future prospects

Plastics could be used in the future and there is a lot of research in this field to improve the power densities, accuracy and refining of crowning and profile modification are adding to the noise reduction goals. Plastics with reinforcements are researched to withstand higher temperatures and have higher strength.

5 Results and Discussions

The results obtained in the thesis is presented and discussed as theoretical concepts, since actual simulations and calculations were not a part of the scope of the thesis. Apart from the concepts, suggestions to improve the geartrain layout and the competitor benchmarking is discussed as well. The concepts, improvement potentials and the competitor benchmarking are suggestions and a pre-study to Volvo for development of a future timing gear system.

5.1 Component oriented concepts

5.1.1 Utilization of scissors gears

The backlash parameter is a necessity for the gears as discussed earlier (see chapter 4.3). The backlash is essential in a gear, but also allows a rattling motion to take place. Hence this motivated a possibility to use scissors gears. Thereby a concept to eliminate the backlash is proposed.

A scissors gear is one of the solutions to eliminate backlash and consequently gear rattle caused between the gear meshes. As the name suggests it acts like a “scissor” and compensate for the backlash between the meshes. Scissors gears were invented almost 30 years ago, but it is not so widely used in many engines. The reason for this might be cost and weight, but the cost aspect could be reduced for the whole geartrain system by using cheaper and suitable material as a substitute for steel.

5.1.2 Concept description

Scissors gears or anti backlash gears are generally a set of two gears. The two gears are mounted on the same axis, but a gear is mounted on the shaft directly and the other gear is mounted on the same shaft but with either a bearing or a bushing. Pre-compressed or preloaded springs are placed between the two gears to enable relative motion between the gears and to take up the shocks, if generated. Hence by the relative motion of the gears the backlash is eliminated and thereby the gear rattle can be avoided.

The spring force and the stiffness is a very vital parameter for the proper functioning of a scissors gear. The preload force is also an important parameter to set. The initial load exerted on the spring in the anti backlash gear may be expressed as;

$$T= k\delta dn \tag{5.1}$$

Where T is Initial torque [Nmm], k is spring stiffness [N/mm], δ is initial deflection f the spring [mm], d is the distance between the center of the gear and the axis of the spring [mm] and n is the number of springs. [59]

The scissors gear can replace the idler gear or a gear in the system but should have the same gear parameters and the specifications as the idler gear. There are a number of types of scissors gears which are available in the market.

5.1.3 Torsion spring system

A torsion spring is used to connect the gears and the relative motion between the gears is absorbed by the torsion spring, see Figure 5.1: Torsion spring. A scissors gear having a torsion spring is depicted below. One of the gears is connected to one end of the spring and the other gear is fixed to the other end of the spring as shown in the figure A lock ring or a retaining ring is placed in order to ensure the that the lash control gear is in place. This type of scissors gears are found on the lower and medium duty Cummins engines and most of the motorcycles which uses a geardrive.

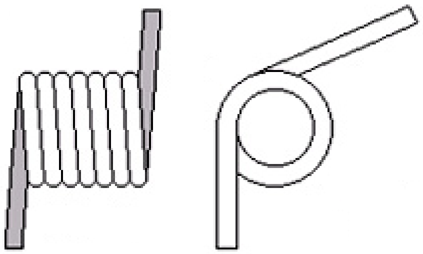
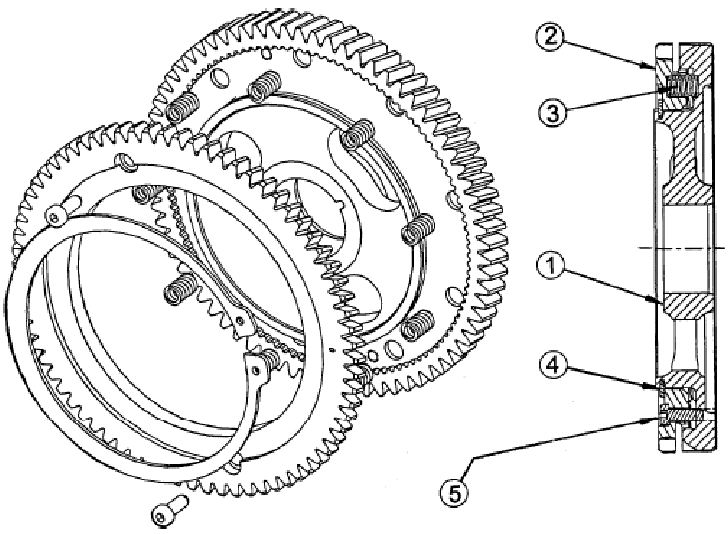


Figure 5.1: Torsion spring



1 – Cam Gear 2 – Back-Lash Control Gear 3 – Springs
4 – Retaining Ring 5 – Screws

Figure 5.2: Cummins 4B torsion spring anti-backlash gear [60]

5.1.4 Radially arranged springs

The gears are arranged with springs positioned radially, see Figure 5.3: Scissors gear springs. One of the gears has a projection which is used to cause deformation of the spring. Both gears move relative to each other and this motion is facilitated by placing one of the gears on a bushing. In order to facilitate the relative motion, one of the gears is fitted on the shaft and the other, as mentioned earlier, is mounted on a bushing or a bearing (see : Scissors gear, front view Figure 5.5). This type of scissors gears are found on the Cummins ISX engine for an idler and an injection pump gear.

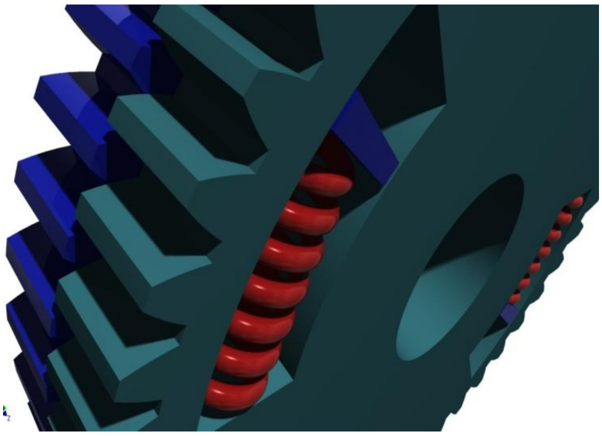


Figure 5.3: Scissors gear springs

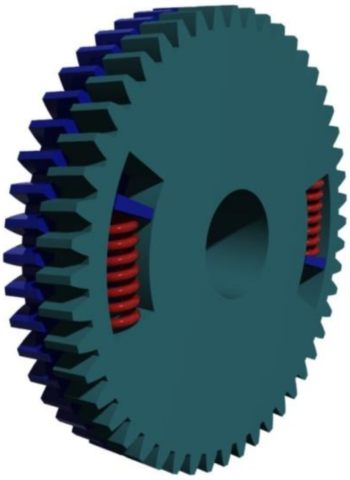


Figure 5.4: Scissors gear, front view

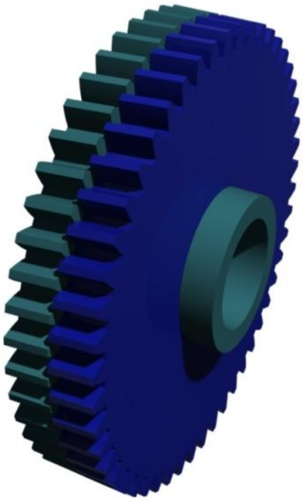


Figure 5.5: Scissors gear, rear view

5.1.5 Gears with an elastomeric material

The gears contain an elastomeric material between the gears in order to facilitate relative motion between the two gears. The elastomeric material could be rubber or any other available material. The main concern is the elastomeric layer in between the gears. It might wear off after a period of service and hence has to be replaced. Thereby this type is not as reliable as the spring type scissors gears and is also not widely used.

5.1.6 Seeger rings

Some anti backlash gears use seeger rings between the gears, see Figure 5.6. For narrower gears it might not be possible to fit springs or it could be a problem in producing the required amount of torsioning. In this case a seeger ring could be used because it utilizes minimal amount of space. The seeger ring is like a lock ring which is used to connect the two gears. One part of the ring is fixed in one split of the gear and the other part of the ring is fixed on the lash control gear. The relative motion between the gears is facilitated by the seeger rings, see Figure 5.7.

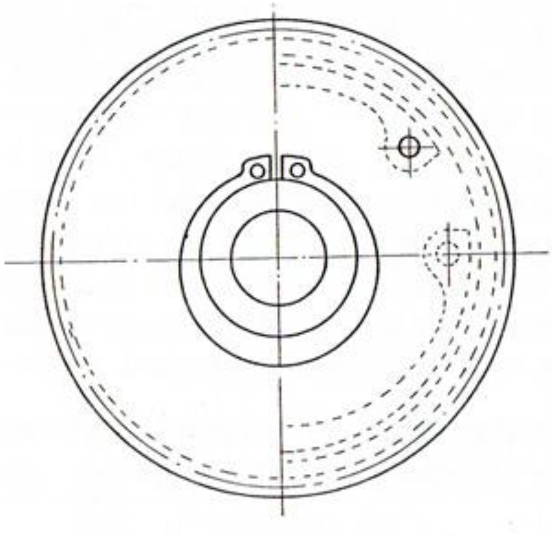


Figure 5.6: Gear with seeger ring inserted [18]

Figure 5.7: Seeger ring

5.1.7 Advantages and disadvantages of scissors gears

Some advantages of scissors gears are stated below:

- Eliminates backlash across the geartrain because of relative motion between the gears
- Reduces noise
- Easy installation, can just replace the stock idler gear available
- Manufacturable and available in the market

Some disadvantages of scissors gears are stated below:

- Expensive
- Heavy because of presence of springs and bolts and retaining rings
- The design increases complexity
- Concerns about the spring life after a period of time

5.1.8 Engines in which scissors gears were used

- The Cummins ISX engine uses scissors gears for their injector pump gear [97]
- Man D engines uses scissors gear for their camshafts [91]
- PTO units for agricultural tractors [59]
- Honda bike engines uses scissors gears [81]
- Toyota engine used scissors gears for their camshaft gear [2]

5.1.9 Future prospects of scissors gears

Current engines already utilize scissors gear to control the backlash and eliminate rattle. There is a possibility for Volvo engines to use scissors gears for the camshaft gear or any idler gear appropriately. Cost and weight is one major factor which affects the usage of anti backlash gears for the geartrain. The cost could be lowered by either using cheaper and suitable materials for the timing gears. The main usage of scissors gear could be for the camshaft gear in engines with unit injectors, but it could also be used for some auxiliary components as well. It is a good solution to use scissors gear in the future engines in order to govern backlash and reduce gear rattle. The usage of anti-backlash gears has a positive impact on noise generated and the longevity of the gears.

5.2 Material Concepts

In this chapter the possibilities of using alternate materials and manufacturing processes are discussed. The advantages and disadvantages from different aspects are considered, as well as previous and current fields of applications are brought up.

5.2.1 Austempered ductile iron gears

The basic idea of using the material ADI evolved when evaluating materials from a weight and cost perspective. Suitable alternatives to steel in terms of noise, weight and cost were being explored. A material found to be a challenging competitor to steel was ADI.

This basic idea initiated a search for information and details on the possibility whether ADI can be applicable for heavy duty timing gears instead of nitrocarburized and case hardened steels. The information gathered provided a motivation to propose a concept with ADI timing gears since it has most of the properties similar or better than timing gears made of steel. ADI can be used either for the whole of the geartrain (depending on the stress level permissible and other factors) or only for a few gears depending on the loading and stress situations.

5.2.1.1 Economical advantage

ADI components have to be produced by casting process with technically advanced machines and skilled labor. As discussed earlier, the casting process is very crucial in order to avoid tensile residual stresses, cracks and defects. Energy utilization is one of the most important aspects to consider in developing a low cost concept.

ADI is casted by near to net shape manufacturing process which utilizes less energy. It is an economical saving from the energy segment. Since the ADI manufacturing process produces near to net shape components, some additional manufacturing and hobbing processes can be avoided. Hence, the overall costs are thereby reduced.
Table 5.1 below depicts the embodiment (commercial energy utilized to bring a material from start to the market until disposal) of energy for different materials. It can be seen from the table that ADI uses lesser energy per unit mass (MJ/Kg) of energy compared to the rest of the steels. [84]

Table 5.1: Embodiment of energy for different materials [61]

Material	MJ/kg
Wrought Aluminum (Primary, average)	255
Copper (average)	151
Structural Polymers (Primary, average)	84
Magnesium (average)	80
Stainless Steels (average)	79
Rubber (average)	70
Cast Aluminum (Primary, average)	58
Plain Carbon and Low Alloy Steels (average)	51
Structural Polymers (secondary, average)	42
Malleable Iron (average)	35
Glass (Primary, average)	30
Austempered Ductile Iron (ADI) (average)	30
Ductile Iron / CG Iron (average)	26
Cast Aluminum (secondary, average)	23
Gray Iron (average)	23

Figure 5.8 depicts a graphical representation of the energy savings only from the manufacturing processes. The manufacturing process of producing steel is compared to the manufacturing process of ADI and it is observed from the bar chart that there is a clear saving of energy and hence it is economical and more sustainable compared to steel.

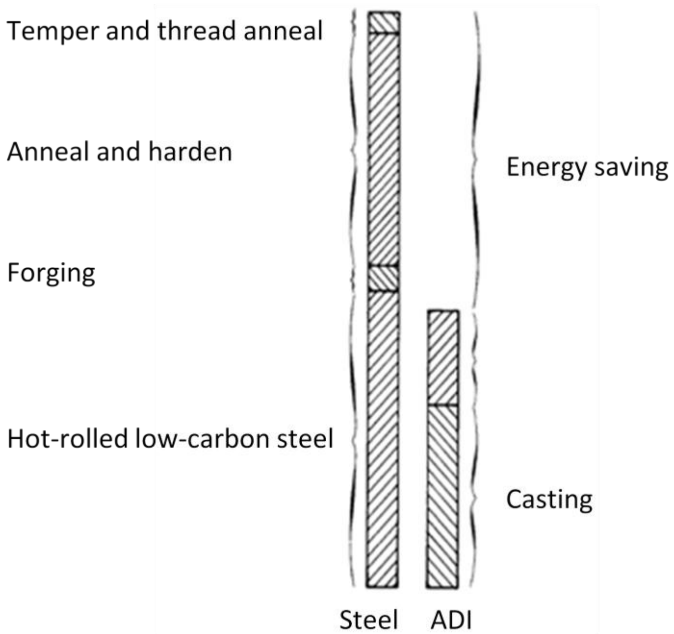


Figure 5.8: Energy savings from manufacturing process made by GM for hypoid gears [34]

In the future there will be concerns about production, consumption and utilization of energy in an efficient manner. Taking the energy effects into consideration ADI is a superior material compared to steels in terms of energy utilization.

The components depending on the required grade (except grade 1 and 2) are machined before austempering the component. By this way the material is machined mostly in a ductile iron form which is in a softer condition, hence improving tool life and thereby reducing cost. This also helps to decrease lead time and leads to faster machinability of ADI with reduced tool wear. [33]

5.2.1.2 Noise perspective

ADI gears generate less noise compared to the steel gears currently used. The main reason for the damping capability of ADI gears (see chapter 4.7.2.3) is mainly due to the presence of spheroidical graphite in the metal matrix.

The gear rattle which results in the creation of vibrations and noise in the geartrain can be reduced drastically with ADI gears, see Figure 4.17. The internal vibrations caused from the steel gears has to be reduced or eliminated by adding retaining rings or lock rings by creating a groove on the gear hub. Hence this leads to increase in costs for rings and for additional machining on the gear hub. All the above problems can be solved by using ADI, since ADI has superior internal damping and does not require additional parts or extra machining. [62]

5.2.1.3 Advantages

ADI is 10% less dense than steel (due to presence of graphite), hence ADI is approximately 10% lighter than steel [61]. ADI offers better scuffing and pitting resistance compared to steels. In conditions due to reduced or failed lubrication, because of its graphite content, ADI can provide a self lubricating effect. Moreover ADI has a lower elastic modulus, thereby lowering contact pressure and for this reason ADI gears have lower coefficient friction. This leads to lower running temperatures and thereby higher efficiencies. Hence lower grade of lubricants are sufficient for ADI gears. Since lower grade of lubricant are sufficient, it is also an economical advantage. [84]

5.2.1.4 Case studies

Mitsubishi Motors

A test was conducted on development of ADI timing gears by Mitsubishi Motors Corp. for a light duty truck. ADI was chosen owing to its excellent mechanical properties, lighter weight, damping capacities, noise reduction capabilities and superior pitting resistance, compared to nitrocarburized steel. An idler made of steel was replaced with ADI (see Figure 5.9) and the tests were conducted and the results were obtained. According to the results, ADI drastically reduced the engine gear noise by almost half and as a result obtained a reduction of 0.7 [dB], only by replacing the idler gear. Moreover the vibration was also reduced throughout the geartrain and also the idler provided internal damping capabilities.

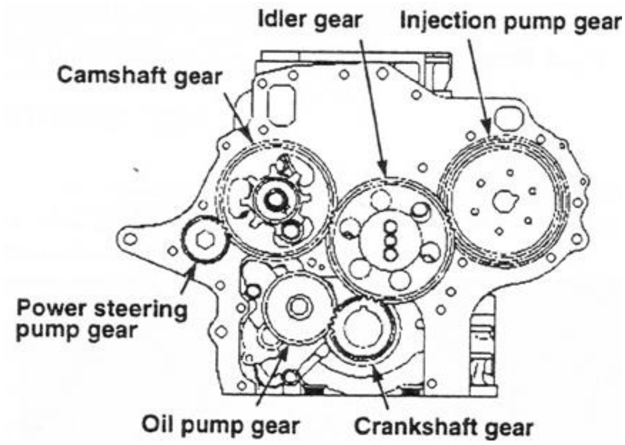


Figure 5.9: Timing gear layout with ADI idler gear [62]

It was observed that ADI offered superior pitting strength. The test was conducted on an engine with S58C nitrocarburized steel gear and an ADI gear on an engine set up. It was also observed from Figure 5.10 that ADI gears produced less noise compared to nitrocarburized gears. The results also showed that pitting occurred on all the teeth on a nitrocarburized gear whereas no pitting occurred on ADI gear tooth. Moreover as depicted in Figure 5.11, it is seen that shot peened ADI gear offered a higher tooth root bending fatigue strength compared to nitrocarburized gears and less but still competitive strength compared to SAE5120H carburized gears. [62]

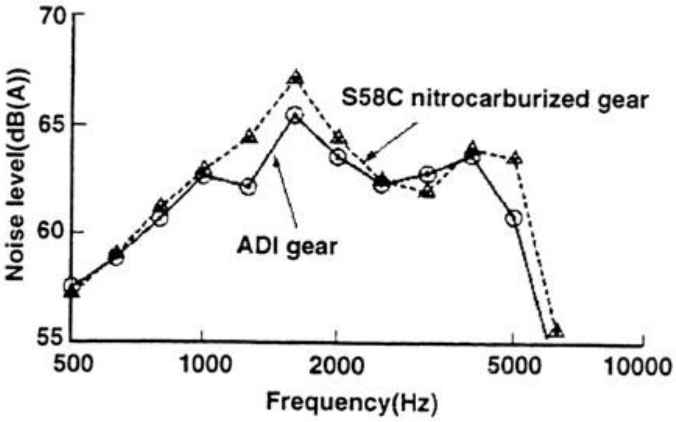


Figure 5.10: Gear noise spectrum [62]

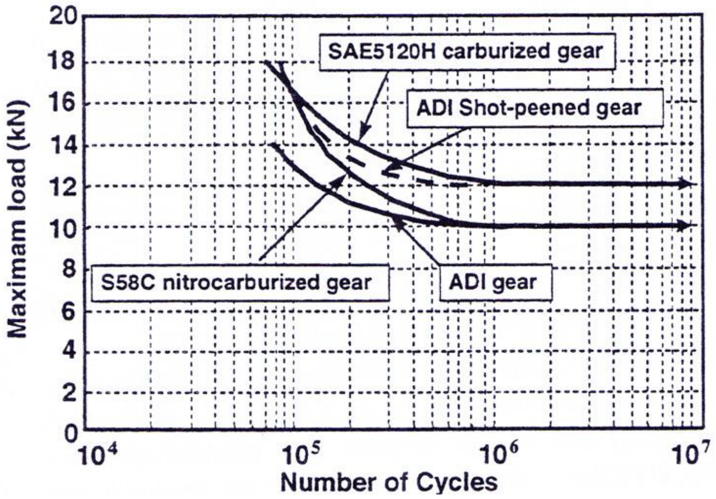


Figure 5.11: maximum load vs. number of cycles for ADI and steel gears [62]

Cummins B-Series

The Cummins B series engines are present from 1984 till today. Currently the B series engines are referred as ISB engines. The ISB engines are all inline six-cylinder, turbocharged diesel engines. ADI timing gears were started to be used for the Cummins B-series engines from 1984. The process has gone through a lot of modifications but still Cummins might use ADI for their timing gears. ADI was used to replaced the forged and case carburized 1022 steel in the Cummins timing geartrain with 30% cost saving. The Figure 5.12 below shows the timing gear layout of the Cummins b series engine where ADI is used for the gears. [92]

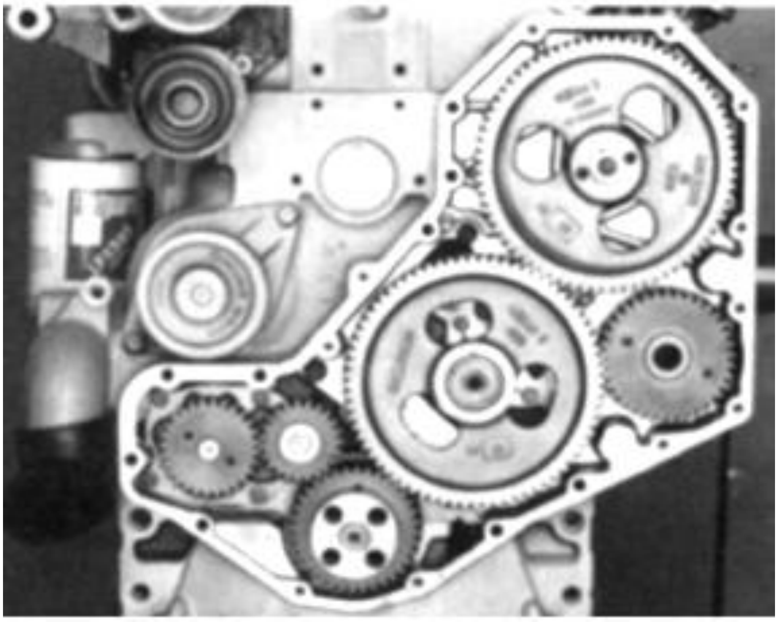


Figure 5.12: Timing gear layout of Cummins B series engine [92]

5.2.1.5 Disadvantages

Casting defects may be prevalent if the components are not cast with use of advanced technologies and equipments. Moreover non destructive testing methods can be used for internal structure analysis.

ADI is only competent to steel in bending and contact fatigue strength, hence cannot be directly replaced. Steels can be replaced with ADI if the range of the grade of ADI used is suitable and sufficient for the application. The main reason for ADI having less strength is due to its lower elastic modulus. The production of ADI grades is highly temperature dependent and needs immense expertise. [84]

5.2.1.6 Future prospect and application of ADI for timing gears

ADI is a suitable alternative for steels in usage for engine timing gears. ADI is a material which is very competent to carburized steel and superior to nitrocarburized and could be used as timing gears for light, medium and heavy duty timing gears. The timing gear train with ADI gears is a good investigation for future geartrains. Many grades of ADI is available (see chapter 4.7.2.4) and the most suitable grade according to the application can be used. ADI has a higher prospect to be used in light and medium duty engine gears. For heavy duty timing gears more research and investigations has to be done to reach conclusions. But in heavy duty vehicles ADI can be used in parts and components which suffices to the fatigue limits and if it satisfies other important properties. The usage of ADI gears could be a suitable concept with respect to weight, cost and noise.

5.2.2 Powder metallurgy concept

Powder metallurgy is an additional process that was considered for manufacturing gears. In this chapter the possibilities of using powder metallurgy for improvements from different aspects are studied. The idea of using a PM material was first introduced due to its internal damping properties. It was, however, realized that the PM process allows for many other advantages than internal damping. The properties of powder metallurgy are considered from three different perspectives; economical, noise and weight.

5.2.2.1 Economical perspective

The cost of traditional gear manufacturing processes is to a large extent affected by the required machining operations. The PM process, to some extent, eliminates the need for machining. Thereby, it gives a significant reduction in production costs through producing near net shape parts. Sizing and final shaping of the PM parts might be required depending on the application, but is much more economical than the required machining of wrought steel gears. The control of material and energy wastage makes PM a very interesting production process from an economical point of view.

As seen in Figure 5.13 (sintering) the PM process has a very high raw material utilization owing to its near net shape production. In this comparison made by the European Powder Metallurgy Association (EPMA) the PM process has the lowest energy requirement per kilo gram of the finished part. The economical advantages of the PM process are greater than the other processes. This is by looking solely at the possible energy savings made, which is only one aspect of cost reduction possible.

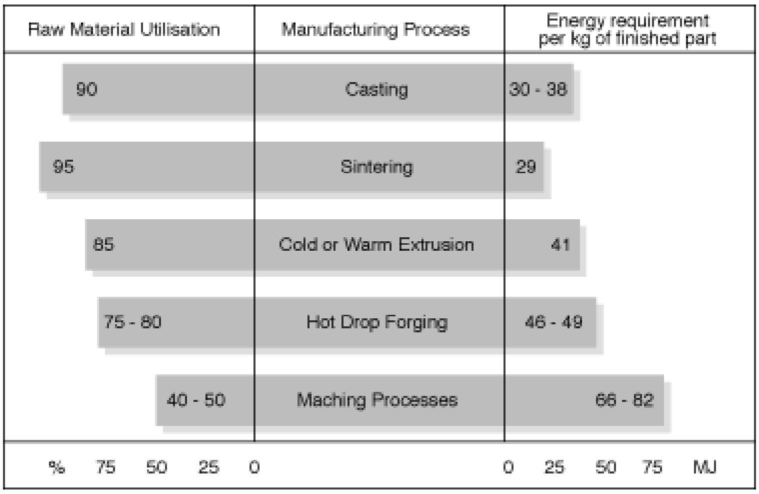


Figure 5.13: Raw material utilization and energy requirements of various manufacturing processes [86]

The number of steps required to go from raw material to complete part is one more factor that significantly affects the production costs. A comparison made by EPMA showed a reduction from 17 to 7 steps by using PM to produce the same part (see table 5.2 and 5.3). Here a total energy reduction of 43% could be reached. Less manufacturing steps is also a result of features in the design of the gears that can be built in to the die to create e.g. holes in the axial direction.

Table 5.2: Energy consumption of the different steps for the PM process [86]

Material: Sint D-11		Finished part weight: 312g	
Anual requirement: 60000 Units		Used weight: 328g	
		Material loss: 16g	
Work Plan	**Machines**	**Energy kWh / Piece**	**Energy as % of total energy expenditure**
Pressing	Powder Press 180 t	0,061	2,14
Sintering	Belt furnace	0,188	6,6
Pressing	Sizing press 360 t	0,066	2,32
Tumbling	Vibratory grinding drum	0,018	0,63
Hardening	Chamber furnace	0,778	27,33
Washing	Washing machine	0,018	0,63
Grinding	Internal round grinder	0,114	4
		1,243	

Table 5.3: Energy consumption of the different steps for forging and machining [86]

Material: 16 Mn Cr 5		Finished part weight: 300g	
Anual requirement: 60000 Units		Used weight: 560g	
		Material loss: 260g	
Work Plan	**Machines**	**Energy kWh / Piece**	**Energy as % of total energy expenditure**
Shearing Off	Hammer Shears	0,011	0,39
Annealing	Annealing furnace	0,04	1,4
Preforging	Drop hammer	0,787	3,05
Finish forging	Forging press	0,298	10,47
Hot deburring	Shears	0,01	0,35
Annealing	Annealing furnace	0,097	3,41
Descaling	Jet unit	0,024	0,84
Sizing	Sizing press	0,154	5,76
Grinding	Single pulley drive-flat grinder	0,2	7,02
Boring	Deep hole boring machine	0,578	20,3
Counter sinking	Boring machine	0,053	1,86
Broaching	Broaching machine	0,077	2,7
Milling	Milling machine	0,108	3,79
Hardening m/c	Furnace	0,609	21,39
Clearing	Rotary table radial operator	0,003	0,11
Grinding	Rotary table radial	0,147	5,16
Grinding	Internal grinder	0,341	11,99
		3,537	

An analysis can also be made of the energy consumption of the different manufacturing processes within the PM gear production. The different pressing procedures used can be evaluated in terms of energy consumption to determine the most beneficial way of producing a specific gear. By adapting the density of the gear to the task, and thereby the manufacturing process, both weight and costs can be reduced. The lower loading on e.g. an auxiliary device gear requires less pressure to produce in the pressing process and hence less energy will be consumed. Lower densities also require less material to produce a part of the same dimensions, hence decreasing the raw material use.

A uniform design that would previously have been made in two or more separate parts could be one additional way of reducing manufacturing costs. This allows designers to think in new ways of achieving the same mechanical function with fewer parts.

In order to achieve the full benefits of PM manufacturing the tooling costs need to be considered. Large parts like the gears in the engine geartrain put high demands on the tools. The dimensions, design and density desired from pressing process has a big influence on the pressure required and hence the tool size. The tool costs might for this reason be increased and needs to be considered for attaining whether or not the PM process for a known production volume will be beneficial. The PM process requires a large initial investment, but will for the reasons previously stated be regarded as a way to reduce costs.

For very big parts, and very high pressures it might be required to re-press and/or re-sinter the part to achieve the desired mechanical properties. This additional densification can be very costly and in some cases redundant. An alternative to a fully dense microstructure is to apply different kinds of treatments to strengthen the gear, specifically in the highly stressed regions. Surface densification is one option for achieving this (see chapter 4.7.3 - surface densification). It allows for higher strength in the surface of the gear tooth and concurrently maintaining the porosity in the core of the gear [63] [64]. Consequently, a surface densified gear could be used for highly stressed applications without the need of reaching fully densified microstructure. This allow for gears produced with lower cost manufacturing to be enhanced and broadens the field of application for lower density PM gears. [65]

5.2.2.2 Noise perspective

As described previously (see chapter 4.4) due to impacts between the gear teeth, vibrations and noise is produced in the timing system. The idea of using PM gears was first risen due to the internal damping properties of porous microstructures. The dampening properties are often stated as an advantage of the PM material's microstructure. In order to propose PM as an option for reducing noise further research had to be done.

The internal damping characteristics of PM was investigated in [66]. It was found that the damping property of PM materials is related to the density, or more precisely, to the amount of residual porosity. The reverberation time for a dense powder gear (low residual porosity) is shorter, which implicates that a porous structure indubitably has a dampening effect.

The measurements in the study revealed that reverberation time will vary for different densities. The increase in density was shown to give a longer reverberation time for a given excitation. Since all other parameters are kept constant the measurements gave a verification of the dampening effects due to pores in the material. Moreover, the effect of sintering temperature, curing temperature and carbon content was investigated.

It is clarified that in order to obtain an increased level of internal damping, pores are needed to be present. Even though the residual porosity is often only a matter of a few percent, only a small amount of pores will significantly abate the mechanical properties of the gear, as mentioned in chapter 4.7.2.3. The main running timing gears, i.e. the gears connecting the crankshaft to the camshaft, are subjected to relatively high loads. The mechanical properties of these gears are of highest priority and thus any residual porosity, to a higher degree, clearly has to be avoided. This reduces the possibility of using porous PM gears for introducing internal damping. However, the gears coupled with auxiliary devices are examples of gears that could benefit from such a change in material, although, it needs to be further analyzed. A study can be focused on which of the gears in the geartrain are subjected to low loads and could benefit from a porous structure and how that would affect the total noise emissions.

To determine if the noise reduction can be observed from a more practical perspective in a full scale test, a gear in the gearbox was exchanged to a PM gear. The gearbox belonged to a Smart Fortwo [66]. From this experiment no significant indication of noise reduction could be seen related to the effect of the PM internal damping. This result would indicate that the noise reduction due to dampening in the gears would be negligible compared to noise from components like bearings and other surrounding components. In order to completely rule out the noise reduction potential of porous PM gears, simulations and/or similar full scale tests are needed for an evaluation of the effects in the engine geartrain. The gear hammering impacts differ from the rattle (if rattle is present in the specific gear box used in the WZL test) and may give different results. The force induced hammering noise involves higher energies from the torque variations in the camshaft gear, which might give a more evident effect.

Surface densification

As previously mentioned, surface densification is one way of attaining high mechanical properties in the surface region. The technique could be one way of maintaining a porous structure granting some level of internal damping as well as a surface with high fatigue properties. This could be considered as a way of using a relatively porous material for more high stressed applications. The noise reduction in such gears may however be more related to the surface finish rather than the residual core porosity. A fine surface finish with a low amount of asperities will reduce the amount of noise produced in a sliding gear mesh. This might be the reason if a reduction of noise is achieved with surface densified gears [67]. Gear rolling is described in [63] to be an effective way of achieving a good surface finish. The study implicated that the surface roughness was improved on the gear surface, compared to a shaved equivalent.

Thermal expansion

The amount of backlash in the gears has previously been linked (see chapter 4.4) to the noise level produced from the inevitable hammering due to camshaft torque variations. It is thus desired to reduce this backlash. However, as mentioned in chapter 4.3, the backlash is necessary to ensure a smooth operation. The backlash is necessary in the design and is considering thermal expansion of the material due to high operating temperatures, lubrication, as well as manufacturing errors. The powder metallurgy technology allows for producing gears with close dimensional control at an economically lower level. Since the thermal expansion of ferrous materials is a factor considered in the design of the gears, there may be an opportunity for improvement. The nature of the operating environment of an engine makes this an interesting topic. Operating temperatures affects the materials used for the engine components and needs to be considered. By combining the economical and alloying potentials of powder metallurgy one additional noise reducing possibility may be available. The idea was to find out if it would be possible to control the thermal coefficient of linear expansion using a specific alloy or from a variation in porosity.

Studies have shown that the effect of residual porosity to some extent has an effect on the coefficient of thermal expansion. In [68] this relation is theoretically and experimentally studied. It was shown that the thermal coefficient of linear expansion is reduced with an increase in residual porosity of, in this case, iron, copper and tin. The reduction of the thermal expansion is increased to a certain optimum level of residual porosity, and is then decreased (see Figure 5.14).

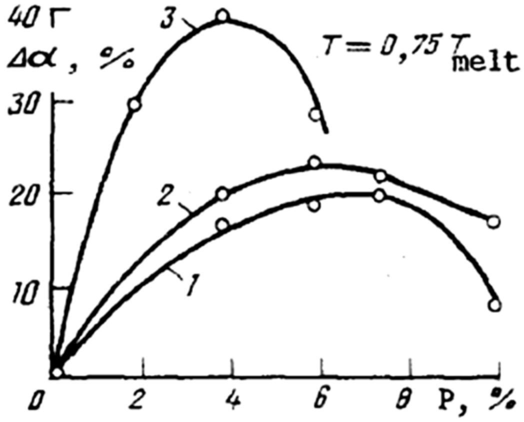


Figure 5.14: Level of reduction in the thermal coefficient of linear expansion of iron (1), copper (2) and tin (3) in relation to residual porosity [68]

Contradictory to [68] the effect of porosity on thermal expansion is said to be negligible in [69]. In this study it is clearly shown that the porosity does not have any significant link to the thermal expansion of sintered parts. This was explicated by stating that the geometry of the structure is consistent and will grow uniformly independent on density. Specimens of different densities ranging from 5% to 23% residual porosity where tested for a large range of temperatures.

The alloying possibilities for powder metallurgy manufacturing might give an option not only from a mechanical property point of view, but also for physical properties like thermal expansion. Since thermal expansion is a material constant the alloying possibilities of PM might play a significant role. The lack of knowledge in the science of materials restricts the understanding and possibility to be analytical in this matter. The thermal expansion of the materials could nevertheless be considered for future research.

5.2.2.3 Weight perspective

The design of a gear can be improved to reduce the amount of material required for a specific loading case, in order to reduce the total system weight. A similar optimization may be possible by using PM gears in the geartrain. The idea was to reduce the weight of the system by using gears with a less dense microstructure, hence using less material for the same application. As stated in chapter 4.7.3.2 the mechanical properties of PM gears are related to the density and is regarded a restricting factor.

The theoretical weight reduction for a specific gear can be estimated only when the final design and the appropriate alloy has been determined. Given that the gears in the geartrain are subjected to different loads, the possibilities for weight reduction will alter from gear to gear. As mentioned earlier, gears coupled with auxiliary devices are not subjected to the same type of loading as the main running gears. Hence, the mechanical properties of these gears need not be of the same magnitude as those which transfers the highest loads. Consequently, a higher amount of residual porosity might be tolerable. By producing a relatively porous core and applying surface treatments this strategy might be possible even for applications with higher stresses involved. [70]

The possibility of using low density gears may be of higher interest depending on the injection system used. The main objective of the torque transferred from the crankshaft to the camshaft via the geartrain is to build pressure in the unit injectors. Hence, the gears are designed in order to take high torque. Introducing a common rail injection system would reduce the loading on the majority of the gears. This leaves space for weight reduction, where PM can play a significant role in both design and variation in the macrostructure of the materials.

As previously mentioned the PM process gives the opportunity to create features in the gear design into the die. The gear designer has the possibility to explore new possibilities that were not possible or economically achievable by other manufacturing methods. The gears can thus be made with e.g. non-round holes and features. This in turn save weight but at the same time maintain the strength of the design and increased material utilization.

5.2.2.4 Case studies

The usage of PM parts is very widespread in different industries. The automotive industry could be considered as the most evolving of the industries for application of PM parts. However, the heavy duty segment of the automotive industry has not yet incorporated this technology into their systems.

Experiments have been conducted to evaluate the possibilities of PM gears in comparison with the currently used wrought equivalents. The study in [94] was conducted by Höganäs AB in cooperation with Scania CV AB. Gears manufactured from PM were tested for a planetary gear from a Scania heavy duty gearbox. Certain compaction processes and surface densification methods where used in order to evaluate the differences in mechanical properties between these PM production techniques for a gear design that is already in use. From this study it was concluded that the PM technology can be used to obtain higher tooth root fatigue endurance limits compared to a wrought equivalent. The warm compaction and surface densification techniques would result in a satisfying increase in mechanical properties. Studies like this shows that the PM technology is developing and finding its way even into the heavy duty industry.

There is a vast amount of PM gear tests available. Different designs and manufacturing techniques have been studied and much information regarding mechanical properties as well as design guidelines considering the manufacturing has been compiled. Due to the lack of published studies as the one mentioned above, it is clear that the PM technology is still in a need for component testing, especially in the heavy duty vehicle segment.

5.2.2.5 Databases and standards

PM database

The mechanical property data values needed to ease the design of a new PM product should be easily found and available for design engineers. With this in mind the Metal Powder Industries Federation has announced a database that gathers mechanical data from contributing companies all over the world. The database, “Global Powder Metallurgy Property Database”, is free to access.

MPIF standard 35

For further information regarding the mechanical properties of PM materials a standard has been developed by the “Metal Powder Industries Federation” and is known as “MPIF Standard 35”**.** It contains physical and mechanical property design data to be used by design engineers. The guidelines are entirely voluntary and are only intended as guidance along with presenting and clarifying the properties and limitations of PM technology for different businesses. [87]

5.2.2.6 Limiting factors

A design engineer experienced in developing gears for a certain manufacturing process is required to understand the limitations and design differences of the PM process. The different manufacturing steps generate particular demands on the gear design. The size will change during sintering and other parts of the manufacturing process and has to be predicted. However, the later mentioned factor is mostly to be controlled by the gear manufacturer rather than the gear designer.

As mentioned previously (chapter 4.7.3 - Compaction), the length of the part will affect the compressibility of the powder. Thereby the length/width ratio has to be controlled. According to EPMA [86] the ratio is recommended to be kept below 3:1. Other dimensional guidelines/restrictions, according to the MPIF standard 35:

- Projected surface area: 32000 mm^2
- Diameter less than 185 mm, or up to 300 mm for parts with a large bore
- Maximum height of 75 mm and minimum of 1.5 mm
- Height/diameter maximum ratio 5:1, height/wall thickness maximum ratio of 8:1

The height limitations are highly affected by friction between the grains and the die wall. The metal powders do not act like perfect liquids under pressure. This causes nonuniformity in the structure of the pressed part. This effect is further enhanced by the size of the part and is thus a limiting factor that needs to be considered in the design. The pressures needed for a specific part is amongst other factors dependent on the part height, surface area, density required and the tools used. If any of the parameters increase, the pressure required and the tool size will increase with it. The correlation between the previously mentioned factors implies that the required pressure is a variable controlled by many factors. It is also seen from chapter 4.7.3 that the needed pressures will change depending on the pressing technique used. However, by keeping to the guidelines of the PM manufacturers, with respect to the tools available, the part sizes possible to manufacture may still vary. The pressures used can, according to Höganäs AB, be in the order of 600 MPa to 1100 MPa depending on material and the desired density. Further design guidelines can be found in publications by the Metal Powder Industries Federation (MPIF) and European Powder Metallurgy Association (EPMA).

The PM manufacturing process is not only limited by the dimensions of the part, but also the shape. Sharp corners are not recommended due to the wear it caused on the pressing tools. These should instead be replaced with small radii. The minimum part wall thickness is also a variable to consider. With increased part height, the minimum allowed wall thickness will increase. Moreover, the size of the part will change during sintering and needs to be considered as well. These values are dependent upon powder compressibility and press tonnage and may vary depending on the compaction techniques, tools used etc. Some additional disadvantages of the PM process are listed below:

- Density dependent properties
- Initial setup cost is high
- High tool costs
- Dimensional change during sintering, rolling and other parts of the manufacturing
- Cost of powder production
- Not possible to create radial holes

With further analysis of the gears to be produced with respect to the requirements/limitations of the PM manufacturer the possibilities of using this manufacturing technique can, and should, be evaluated.

5.3 Redesigned layout concepts

5.3.1 Eccentric/Elliptic drive mechanism

One of the main sources of noise and vibration across the geartrain is primarily due to the gears. The rattle is produced from the gears and hence transferred to the geartrain as well. Hence an idea came up to reduce/eliminate the number of gears and optimize the geartrain. The basic idea was inspired from a steam engine connecting rod mechanism, but applied to gears at both ends instead of a piston. One end of the connecting rod has a gear and the other end could be a coupling or a rotating device. The crankshaft gear at the bottom is driven by the engine.

By this way the number of gears could be decreased, and hence there is a possibility to reduce the noise and vibration across the geartrain. By reducing the number of gears there is also a possibility to decrease the cost and weight of the geartrain.

5.3.1.1 Concept description

The concept deduced consists of two or three gears totally as seen from Figure 5.17. The camshaft does not necessarily need a gear, it can also be mounted on a circular shaft or disc or any other appropriate device. But this depends on the auxiliary set up. The gears could be spur or helical gears depending on the cost. Helical gears could be much more suitable since it is produces less noise while operation and has a higher longevity compared to spur gears. The gears may be also made up of powder metallurgy gears or ADI gears in order to gain the advantages that the material offers (refer concept ADI and PM). The auxiliaries may be meshed with the bigger idler gear which houses the bottom end of the connecting rod or to the crank gear. The connecting rod as well might be made of P/M or ADI or any other lighter but suitable material. Thereby the overall weight of the entire system will be lower than a geartrain with a lot of gears. Moreover the weight and the cost might be lower because there are lesser bearings and shafts.

The crank gear is placed in the rear of the engine beside the flywheel. A torsional coupling can be provided between the crank gear and the crankshaft to dampen the torsional vibrations. Torsional couplings negate the transfer of vibrations from the crankshaft to the gears.

The connecting rod can be fixed to an appropriate set up behind the idler gear as shown in Figure 5.15 .The number of connecting rods needed to be used can be deduced only after extensive calculations. The method to control the torque on the camshaft to provide proper angular rotation is vital. Hence the number of connecting rods to be added will depend on the requirement. Mostly, either two or three connecting rods need to be added from the crankshaft to the camshaft to govern proper angular motion without irregularities. These connecting rods have to be added on different planes in order to avoid clashing. The other end of the connecting rods drives the camshaft.

Since it is a four stroke engine the camshaft should rotate at half the speed of the crankshaft. Hence this speed reduction is obtained by connecting the crankshaft gear to a bigger idler such that a 1:2 speed reduction is achieved. The cam gear will rotate at the same angular speed as the idler gear since they are connected by means of a connecting rod and since there is no speed reduction between them. The camshaft could be mounted on a journal bearing.

Counterweights need to be added in the camshaft for balancing and preventing vibrations and irregularities. Balancing of the camshaft is very essential in this case because of counterweights. It should be balanced like the crankshaft for different orders of frequency and vibration. The counterweights could be made of ADI or PM or AGI or any other lighter material like the crankshaft in many vehicles. The counterweight might be an additional weight to the system but is mandatory to avoid irregularities. It is a simple mechanism and balancing is very important to prevent vibrations and torque irregularities.

This concept is based on an “outside-the-box-thinking” and needs immense amount of expertise to achieve perfection of this mechanism.

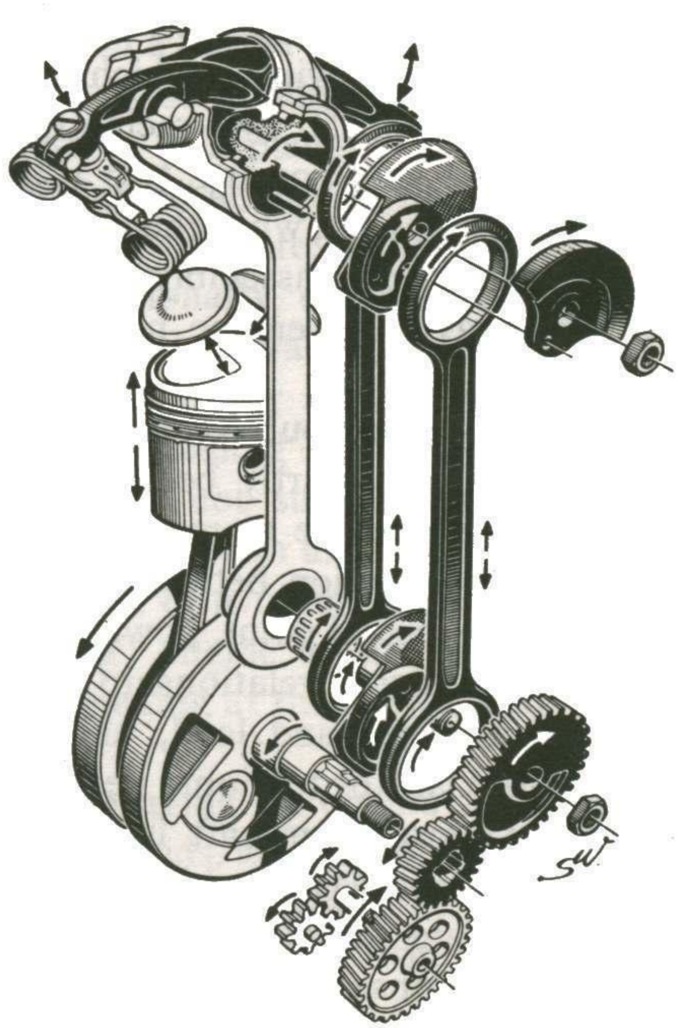


Figure 5.15: Pictorial representation of Elliptic mechanism

5.3.1.2 Concept utilization in existing engines

While exploring the above concept, it was realized that a concept similar to the above deduced concept has already been used in old car and motorcycle engines. Old motorcycle and car engines (NSU, Prinz 4 in 1960’s and Bentley car engines in 1930’s) had applied the concept for cam timing system. In the old NSU max motorcycles the set up was like in the Figure 5.16.

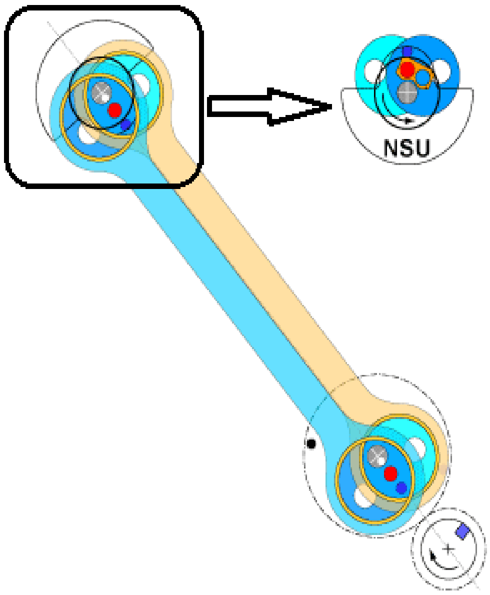


Figure 5.16: NSU cam timing system [93]

The above Figure 5.16 depicts the engine timing configuration from one of the NSU Prinz engines. It is a very simple setup and is very similar to the idea proposed. The main setup has eccentric shafts with connecting rods which governs the valve timing. The above setup has three connecting rods of which only two are shown. The grey dot is the center point connected to the elliptic shafts. The blue dot is the point which connects the two elliptic shafts together and the red dot is used to connect the shafts to the camshaft placed on a journal (as shown in Figure 5.16). It is connected with a brass linkage. A similar setup with modifications according to the heavy duty segment could be used for valve timing system or the basic concept stated could also be implemented but with required validations, calculations, simulations and analysis accordingly. [93]

5.3.1.3 Advantages and disadvantages of the elliptic mechanism

Some advantages of the elliptic mechanism are listed below:

- Less number of gears
- Probably lower cost because bearings, gears and shafts are omitted across the geartrain, could be a low cost concept
- Lower weight potential
- Lower noise and vibration potential
- Manufacturable and usable
- Simple mechanism

The disadvantages of the concept are listed below:

- Counterweight balancing is very crucial and it could add weight to the system
- Not yet tried for heavy duty applications
- The torque balancing is very important since the angular speeds might be different between the idler and the camshaft. Hence these results can be only corrected and proved only with further calculations and validations.

5.3.1.4 Future prospect of using elliptic mechanism concept

The elliptic concept could be a very efficient concept for the future in terms of weight, cost and noise.

It could be possible for this mechanism to work for light, medium and heavy duty engines. Moreover the components for this mechanism can be manufactured. The mechanism is simple and can be perfected for usage of timing. Lighter and tougher materials could be used for the system along with required noise isolators for the system to function efficiently.

The concept thought can be put to use for timing system provided detailed analysis, calculation, design and testing. The concept discussed and proposed inculcates low weight, low cost and less noise concepts respectively into consideration. The above concept, if feasible on timing systems could be a good break through the frontier where geartrains exist.

5.3.2 Bevel gear timing system

5.3.2.1 Basic idea and motivation

The basic idea was to reduce the number of meshes in the geartrain between the gears thereby reducing the friction and power losses. Moreover this might also reduce the gear rattle and noise generated at the different gear meshes. The concept was realized from the differentials and final drives in cars and trucks. Bevel gears are used in differentials and final drives and have a capability to withstand high intermittent loads and torques. Hence a concept possibility was proposed with bevel gears.

The idea to use a bevel gear arose when a need to transmit power at an angle of 90 degree was needed from the crank to the cam. The idea for the concept was to transmit power from the crankshaft to the cam shaft with a simple gear arrangement. Hence a bevel gear arrangement at the crankshaft transfers power to a shaft which then transfers power to the camshaft by a second bevel gear mechanism (see Figure 5.17 and Figure 5.18). The main purpose to propose this concept is because it is a simple arrangement and is an easier solution for a geartrain layout.

5.3.2.2 Concept description

The set up consists of four gears and one shaft. All the four gears are spiral bevel gears and the shaft is placed vertically to connect the two bevel gears. Spiral bevel gears are used instead of straight cut bevel gears because spiral bevel gears have better longevity and can take up higher loads. The loads and thereby the stresses move from the start to the end of a gear tooth for spiral type whereas the stress is always concentrated at a single point for straight type. Hence spiral bevel gears would be a candidate choice for usage. Bevel gears are suitable to take high amount of loads and torques, which is the reason of its use in differentials in trucks and cars. The exact dimensions and parameters of the bevel gear and the shaft are not deduced exactly to fit in an engine because of the limitations of this work, but a figure depicting the system gives a representation of the layout and the amount of torque that could be transferred through the shaft.

The precision of the bevel gears is very important in order to have a perfect timing since approximately 1000 Nm has to be supplied to the camshaft in order to build up the desired pressure in the unit-injector system. Bevel gears are possible since they can withstand high torque loads, but the shaft connecting is very crucial. The shaft could be placed on a journal bearing or a suitable bearing for sufficient support and reducing friction and provide ease of rotation. The shaft is placed inside a shaft-housing. Bevel gears could be a possibility to utilize less space and could facilitate packaging. See the below 3D diagram (Figure 5.17 and Figure 5.18) for a better under understanding of the layout.

Figure 5.17: Full scale bevel gear model for a Volvo 13L engine, crankshaft and camshaft

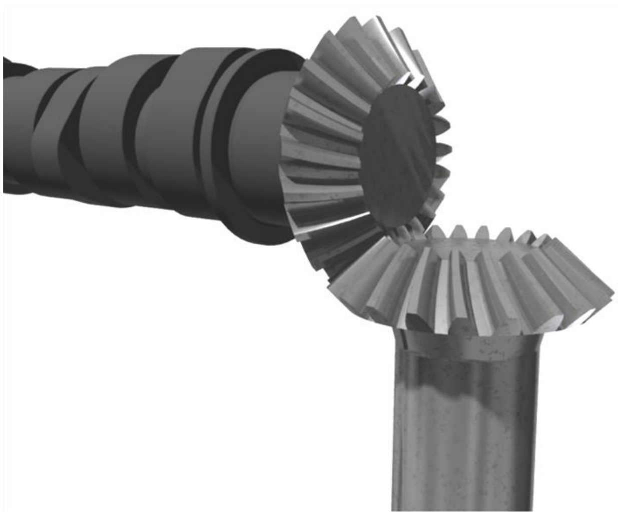


Figure 5.18: Bevel gear model for a Volvo 13L, camshaft

5.3.2.3 Advantages and disadvantages of the bevel gear system

The bevel gear system provides some positive aspects as listed below:

- The number of meshes is less
- Lesser the meshes less is the noise and rattling
- Could be a light weight concept compared to geartrain
- Manufacturable and available
- Could improve packaging provided the dimensions of the shaft
- The shaft could house the auxiliaries as well
- Can take high torques and loads

The negative aspects of the concepts are:

- Concerns with shaft design
- Needs more research, since this technology is not exploited in modern engines

5.3.2.4 Case studies

None of the car engine or truck engine manufacturers have explored the possibility of a bevel gear for a timing system; hence the concept could be a unique possibility for truck engines. After doing some research about bevel gears it was found that some motorcycle engines like NSU, Ducati, Norton etc did feature bevel gears for timing systems earlier, but is very old (see Figure 5.19 and Figure 5.20).

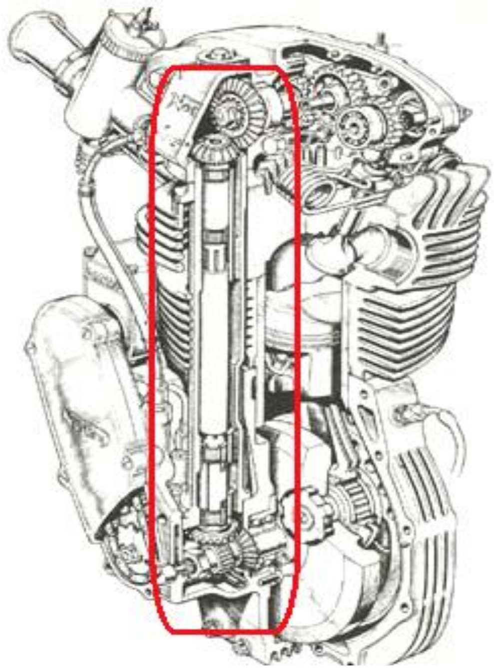


Figure 5.19:Norton 1961 [95]

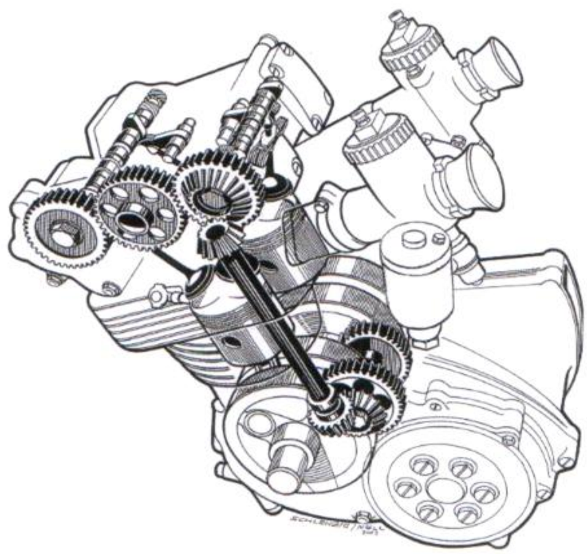


Figure 5.20:NSU rennmax 1954

5.3.2.5 Future prospects

Bevel gears are a good option for a future timing system because of its advantages and its capabilities. Any conclusions on its use can be reached by more advanced calculations, validations and simulations. It could be a solution for timing gears when common rail systems are used, since in that case one need not worry about the opposite torque irregularities produced from the mechanical injectors. Since it is a new concept and not widely in engines, very little information is available regarding its reliability and usage. It could be a good concept to analyze and adapt for the future timing system.

5.4 Layout improvement solutions for geartrain

Important considerations concerning layout with effect on noise, vibration and better packaging are listed below. Some considerations are important in order to reduce noise and vibration radiated across the geartrain. The pre-study of the listed items are important and could be included while developing a concept geartrain.

5.4.1 Loading constant torque devices

Loading devices that utilizes constant torque like coolant pump or alternator does not cause rattle and vibration across the gear meshes, if loaded on the geartrain [71]. However the injection pump is a source of noise and vibration in the geartrain. Therefore a fuel system with low cyclic torque can be used to reduce geartrain noise and vibration. In low cyclic torque systems like the common rail system the demanded torque fluctuations is not varying drastically.

References: [72, 73, 74]

5.4.2 Effects of gear inertia

Large changes in the inertia of idlers might have an influence on gear rattle. The available literature and experimental investigations have contradictory theories about the rattling behavior of gear transmission systems. Inertia can be defined as inversely proportional to the angular acceleration as seen from the following dynamic equation 5.2;

$$T = I\ddot{\varphi} \tag{5.2}$$

Where T is the Torque (Nm); I is the inertia (kgm^2) of the gear and $\ddot{\varphi}$ is the angular acceleration (rad/s^2).

As the inertia increases, the angular acceleration will reduce as the applied force/torque is kept constant. This might have an influence on the tooth impacts and rattle thereby the level of the rattle noise produced. This theory would imply that the increased inertia is making the system less prone to rattle. It can be verified by the various theoretical models in [75]. It is depicted that the inertia of the drive train will improve the rattle resistance. The exciting forces in this example are pulsating between two fixed positive values simulating the pulsating gas forces. The inertia in this system abates the rattling motion caused by the cyclic torsional vibrations. In other words, the initiation of the rattling behavior is resisted by gears with an increased moment of inertia.

A negative effect can be observed by the increase in mass and inertia as the rattling has commenced. As seen in chapter 4.4.2 the noise level of the impact caused by the tooth contact will increase with mass. The model shows that the mass and inertia of the loose gearwheel will affect the noise produced. As the mass of this loose gear increases so does the impact intensity and hence the sound level. This would suggest that the mass of the floating idler gear should be kept at a minimum to decrease the impact forces.

The above mentioned theories propose opposite effects by the inertia on the gear rattle, with focus on a vehicle gearbox. The excitation forces are different for the engine geartrain, as explained in chapter 4.4.3. Consequently, the influence of the moment of inertia of the gears may have different effect on the gear noise. The commencement of the rattling in the engine geartrain is inevitable due to the negative torques caused by the injection system. This would mean that the inertia would not resist the commencement of the rattling due to the forced motion. However, depending which gears examined that are examined the inertia effect could have different impacts. An idler gear would e.g. act differently as opposed to a loaded gear. Further investigations are needed to ensure the effects of the inertia on the engine timing gears. This will aid the assessment to whether it would be beneficial to have less number of gears with larger dimensions to reduce noise. It can be proved by dynamic calculations and simulations and is an interesting parameter to consider.

5.4.3 Phase difference velocity

Phase difference velocity between crankshaft and camshaft is an essential factor to investigate. The phase difference in the velocity between the crank and the camshaft gear with respect to crank angle degree should be minimal in order to reduce the gear rattle. But it is only a concern where the cam and the crank gears are directly connected or connected by means of an idler. It could be a factor to be investigated for the bevel gear concept. [76]

5.4.4 Effect of meshes

The number of meshes between the crank and the cam gears in the geartrain affects the noise produced (see chapter 4.5). An experiment was performed by Caterpillar to modify their old geartrain (see Figure 5.21) to an optimized layout in order to observe the effect of the meshes between crankshaft and camshaft as shown in Figure 5.22.

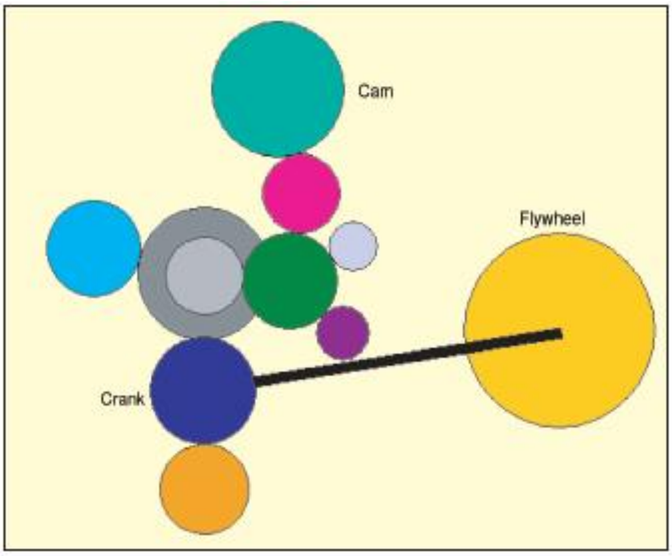


Figure 5.21: Caterpillar geartrain [19]

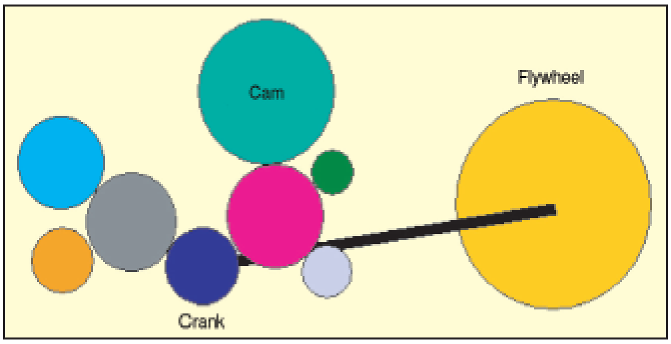


Figure 5.22: Optimized Caterpillar geartrain [19]

Empirical equations 5.3, 5.4, 5.5 and 5.6 were deduced by Cummins in order to predict the noise of the engine geartrain theoretically depending on the number of meshes and position of the geartrain.

Rated 1m level = 93.9dB + 2.6(G-1) + 4.8F (5.3)
Torque peak 1m level = 91.5dB + 2.5(G-1) + 1F (5.4)
Low idle 1m level = 85.9dB + 0.8(G-1) (5.5)
High idle 1m level = 99dB + 1.2(G-1) + 4.8F (5.6)

Where G is the number of gear meshes between the crank and the fuel system (cam shaft in case of Volvo), F=1 for front geartrains and F=0 for rear geartrains as deduced in [72].

Rear geartrain is most suited from a noise point of view when compared to a front geartrain. This fact is also proven by Cummins after they tested theoretically and practically for a set of engines by changing the position of the geartrain from front to rear. An additional advantage of a rear gear train is better packaging.

Reference: [19, 72, 77]

5.4.5 Torsional couplings

Torsional couplings can be used in the crankshaft to isolate crank torsional vibration. These can be placed between the crank shaft and the crank gear to isolate the crank gear for the crankshaft torsionals. Torsional couplings could also be used for other auxiliary components as well if needed to isolate vibrations. [19]

5.4.6 Effect of auxiliaries

The piston type air compressor is one of the major producer and propagator of noise and vibration across the geartrain. In order to reduce the vibration produced from the air compressor the auxiliary gear could have an anti backlash gear to prevent rattle or can be a gear made of ADI such that there are no internal vibrations. Torsional couplings could also be used between the gear and the device shaft.

Modifying mounting points of auxiliary components can reduce structure borne sound and vibration. The vibration is produced from the source but eliminated as noise from panels and mounting points if not positioned properly. It is very important to consider this effect, though the geartrain can be silent but the fastening points can induce sound. This natural frequency of sound generated, if it matches the natural frequency of any other sound source, it might result in resonance and production of harsh noise. Resonance effects of auxiliaries should also be considered. Resonance can lead to production of sharp noise peaks from the system and this can be detected by modal analysis. An auxiliary device could operate at two natural frequency vibration modes and if even one of these collides with the frequency of the meshing gear running the device, this may lead to production of resonance and noise. Hence one must also check for resonance effects. [73]

5.5 Competitor Benchmarking

The timing gear system of the Volvo engines have for a long time followed the same basic layout. The intention of competitor benchmarking in this work was to find out how far competitors have reached in this specific field. The usage of certain technologies with the purpose of reducing noise, cost and weight was especially interesting. The benchmarking study relied much on the accessible published information in databases, as well as the written benchmarking reports available internally at Volvo.

The majority of the larger commercial vehicle companies were of interest in this study. Engines from the following manufacturers where investigated;

- Scania
- MAN
- Mercedes
- Detroit Diesel
- Cummins
- Caterpillar
- Hino Trucks

The majority of the larger commercial vehicle companies were applicable for the purpose of this study. Detailed information regarding the engine geartrain of these companies was mostly not found in published and general vehicle information. A teardown of the engine components would for this reason be required in order to get a good depiction of the technologies used. This has to a great extent restricted the amount of data possible to acquire for this competitor benchmarking. The study has thus been relying on the benchmarking studies done earlier and the hardware available in-house for examination. A great amount of data has also been possible to gather through benchmarking databases. The benchmarking database used in this benchmarking study is; “A2Mac1” [91]. Full teardown reviews are made here and some basic information is provided about the different components. The teardowns are documented in the form of pictures and virtually all parts of the truck are covered.

In-depth material data has neither been available in the databases nor in the available benchmarking reports. Hence, lab tests would be needed for attaining detailed material information and was thereby not complete in this benchmarking study.

A table was constructed from the acquired data where the following points were analyzed;

- Type of cam drive
- Types of gears
- Layout solutions
- Number of meshes between crankshaft and camshaft
- Geartrain location
- Gear materials
- Injection system
- Vibration dampers on crankshaft and/or camshaft

Appendix 2 shows the results from this study. One obvious conclusion is that all companies do use gears for the timing system, with no conceptions. The choice of gears however does vary. The more modern engines mostly use a combination of helical and spur gears, or only helical gears. The benefits of helical gears from a noise and stress points of view have been proven to be more than sufficient to motivate the more expensive production costs. Despite this some companies are still sticking to geartrain layouts entirely consisting of spur gears.

It is observed that the layout does vary depending on engine and make. The majority of the engines studied have in the order of three or four meshes between crankshaft and camshaft. One exception is an engine from Hino Trucks which uses a pushrod system, where the camshaft is driven directly by the crank gear. This will give the possibility to have a more compact engine design. However, it is not favorable from a vibration point of view, and is rarely used in modern truck diesel engines. As mentioned in chapter 4.5(Noise and vibration generation), by decreasing the noise sources, i.e. decreasing the amount of total meshes, will decrease the noise created from the geartrain. It was thereby interesting to evaluate the differences in the geartrain layouts. Additionally, as seen in [72], depending on the position of the geartrain will reduce the measured gear noise. The geartrain is generally positioned in the rear of the engine, with a few exceptions.
The most interesting part of this competitor benchmarking was to see whether companies have specific solutions for reducing gear hammering noise. It was found that at least two of the companies in this study use anti-backlash gears in production of their heavy duty engines. MAN has a solution for their accessory drive gear, whereas the Cummins ISX 600 HP [97] version uses a scissors gear for the cam gear and for an idler gear. Patents have been found for a number of companies where different types of solutions are used to create to an anti-backlash gear. It was realized that the cost aspect of these gears is a restricting factor and may be one reason why more companies are not having this in production. However, it can be interesting to compare this technology to the alternatives, only from a noise point of view. Changing the entire fuel injection system from unit injection to common rail for the purpose of reducing noise could result in much higher costs from e.g. a R&D point of view.

It is important to point out that the data acquired from the available engines on one hand gives a good implication of the technology the companies have been putting into production. On the other hand it does not give real evidence of what their future moves are. For this reason a patent search was carried out to expand the benchmarking for exploring what kind of research the companies are doing in this field. Some of the patents related to the corresponding manufacturer are also available in the table (see Appendix 2 – Benchmarking table). The patents all have the purpose of reducing gear noise. Backlash is the main concern and a common approach can be observed in all the patents. The elimination of backlash is undoubtedly the most efficient way of reducing the gear hammering noise, and is shown through the research and the technology put in production by many of the leading companies.

6 Conclusions

The timing geartrain is a vital set of components in an engine and there is immense potential for improvement in the system. The development potential can be either from a design, cost, material, layout and weight point of view. The conclusions to the thesis are drawn based on the research questions set up from a noise, layout, material, cost and competitor benchmarking point of view. The validation of the proposed measures for noise reduction has to a great extent been limited by the already conducted experiments and available research in the field. Complete validations of the proposed methods are very important in an early concept development phase. In this stage many doors are open for new directions to be taken for future development where the right choice will save both time and money. This thesis has not been focused on one specific field or problem, but has instead dealt with the improvement of Volvo's engine geartrain from a wider perspective. Due to the nature of such studies no direct answers for a given problem can be given. Instead, proposals for possible future research and in-depth analysis are made. It has been found that there is a scope for further studies to be made in majority of the fields this thesis has been involved with. The conclusions from this study are given as answers to the previously stated research questions.

Noise related questions

What are the main sources of noise generation?
The main sources of noise in a geartrain are gear rattle and gear whining. Gear rattling is caused as a result of backlash between the gear teeth and torque variations from the unit injection system (MEUI), where the fuel pressure is mechanically built up in each injector. Some auxiliaries (air compressor, pumps, PTO etc) and position of fastening points also affects the generation of noise and vibration.

How is the current injection system affecting the noise generation?
Volvo uses MEUI which is the root cause of hammering generation in the geartrain. The opposite torque produced as a result of high injection pressures results in noise generation across the geartrain.

How can gear rattling noise be reduced?
The noise to the surrounding can be eliminated by proper isolation of the geartrain. Eliminating or optimizing backlash has a significant impact on gear rattle and noise produced. Identify auxiliary units which could be a source of rattle generation in the geartrain and apply suitable measures to rectify it.

What technologies exist for reducing the noise?
From a gear rattling point of view, different types of scissors gears or anti-backlash gears can be advantageous. Various coatings on the gears (e.g. rubber integrated with metal coating, sacrificial lubricant) has a potential to reduce noise, but needs more research for feasibility with respect to time. The noise generated from internal vibrations can be negated by using different material choices like ADI, AGI and PM that provide better internal damping than steel. Lock rings and retaining rings on the gear hub is also used in order to dampen the vibrations. Torsional couplings between the gear and the shaft can provide good vibration isolation.

Does the material choice influence noise generation?
The material choice plays a crucial role on the noise generated. It can be clearly understood from the material concepts that a change in material affects the noise produced drastically. It is also understood that damping properties of different material varies, which is a primary property to reduce noise. Furthermore, certain secondary treatments (e.g. gear rolling) on gears have a positive effect on noise.

Layout related questions

Does the layout and relative position of gears have an effect on the noise level?
The position and layout of the gears affects the noise generated. Changing the layout by reducing the number of gears will have an influence on noise. The position of auxiliaries in the geartrain is very vital and some auxiliaries induce noise and vibration to the geartrain. The panels and components to the geartrain must be fastened carefully to avoid emission of noise and vibration through them.

Does the number of meshes have an influence on noise?
With fewer meshes, i.e. contact between the gear wheels, the total noise level is reduced. If the number of meshes is reduced the summation of error due to backlash will be reduced and hence the noise.

Is it possible to use bigger gears (with larger diameter) to reduce the number of meshes from a noise-reduction point of view?
In order to reach from crankshaft to camshaft larger gears are necessary to be used if the number is to be reduced. Larger gears increase the size and weight resulting in a higher inertia. It is shown that the increased inertia can have both positive and negative effects on the commencement and effects of the rattling phenomenon.

What possibilities exist for alternative power transmission systems?
The bevel gear concept and the elliptic concept are two alternative power transmission systems, but needs further investigations and calculations. Other power transmission methods may exist which is yet to be explored.

What impact does an alternative layout have on cost?
The layout modification could have an impact on cost. By reducing the number of gears, there could be a cost benefit and if the number of gears is reduced, cost is also saved for omitting gears, bearings, shafts, seals and other mounting points. The alternate layout concept proposed could have a positive impact on cost.

Material and manufacturing related questions

What materials and manufacturing alternatives to steel exist that are possible to use for heavily loaded gears?
Gears made of powder metallurgy, austempered ductile iron, austempered gray iron and plastics could be a suitable replacement for steel gears for light, medium and heavy duty applications depending on the usage, loads and stresses.

Do the alternate materials provide better internal damping properties?
Materials like ADI and AGI offer excellent damping properties compared to steel because of the presence of graphite in the matrix. Moreover, PM could also offer good damping properties but it is related to its density, or more precisely the residual porosity.

Can the material behavior be simulated with available softwares?
PM gears can be simulated using softwares like Zako3D. This software takes the characteristics of the PM material into account for gear tooth analysis.

Weight related questions

Can the weight of the geartrain be reduced by the choice of material?
The choice of material is a very decisive factor to optimize the weight of the geartrain. ADI, AGI, and plastics are lighter than steel and PM is also lighter than steel but depends on the density and porosity and composition of the material.

Can the design of gears be changed to save weight?
The design can be changed to make the gears lighter. Holes can be made appropriately in gears depending on stress and load levels. For PM gears holes of complex shapes can be achieved because of higher design flexibility. Weight of the gears made by PM depending on the application, could be reduced by having a porous core but densified outer surface. Gears with a metal outer layer and a plastic or a rubber hub could be used to save weight.

Cost related questions

How can the cost of the geartrain be reduced?
One of the methods of reducing the cost of the geartrain is optimizing the material usage. Bulk production of PM gears gives cost benefits, on the other hand ADI is also cheaper than steel in large quantities.

How does the manufacturing process facilitate cost reduction?
Near net shape manufacturing of PM and ADI are advantageous because it needs lesser machining operations and hence it provides cost benefits in terms of energy savings. For ADI, reduced tool wear and reduced lead time is possible because ADI is machined prior to austempering.

Competitor benchmarking related questions

How are companies proceeding concerning to noise and cost related to geartrains?
Competitors have invested in research to modify their geartrains from a cost and a noise point of view. From benchmarking and patents it is evident that there is continuous development to improve the geartrain.

What are their plans for future development?
The plans for future development of competitors are very difficult to find out since they are very confidential. No further information could be found in this topic.

Have any of the patents filed been put in production?
Some of the inventions in the patents have been implemented for use in engines. Some patents are not put into production considering the cost and complexity.

7 Future Prospects

The thesis work was performed to reduce gear rattle noise and optimize the layout, weight and cost of the geartrain for the future timing gears. There is immense improvement potential in the current geartrain solution. More research can be done on the material of gears. The affects of damping properties offered by ADI, AGI and PM can be experimented and compared to that of steel gears. The alternate materials suggested for the timing gear could also be analyzed from a weight and cost perspective with respect to existing solution.

Utilization of energy is a major concern for the future sustainability of the manufacturing processes. Materials manufactured by efficient manufacturing process consuming a lower amount of energy is very beneficial. The different materials proposed consume less energy per unit mass for manufacturing in contrast to steel and from the future point of view is an interesting topic to investigate with reducing cost as a concern.

Plastics gears are mainly known for their light weight, silent operation and self lubricating abilities. The possibilities of usage of plastic gears for timing gears has been experimented by competitors to evaluate and compare the noise emanated from a plastic geartrain to that of steels. The feasibility of non metallic gears for engine timing gears of heavy, medium and light duty trucks are an interesting topic to be explored for the future.

As mentioned earlier, a number of softwares are available to simulate only the properties and behavior of the materials and its effects with respect to loads on the geartrain. These softwares can be utilized to study in depth the characteristics of the impact of a material on the gears.

The innovative concepts proposed could be a future timing system instead of a normal set of gears but needs immense study of the feasibility of the concepts by analyzing and validating them further. The elliptic mechanism proposed needs to be re-modified further in relation to the amount of connecting rods needed in order to ensure proper functioning, with respect to torque. The elliptic mechanism and the bevel gears could be innovative concepts from a packaging point of view. It will be a good idea to further explore these concepts in in-depth detail. Several softwares are available that can utilized to perform dynamic simulations of the system and also to analyze the NVH properties. The above mentioned ideas and recommendation for making the concept usable can be a very interesting field to study further for the future.

An interesting topic to analyze is the use of bigger idler gears. The possibility of replacing many gears with a big idler could be a promising study. The consequences from a weight point of view can be a part of the study. This could be a method to reduce the number of meshes and thereby improve power transmission efficiency and reduce noise consequently, presumed that the total weight of the geartrain is kept constant.

There are many types of simpler and usable scissors gears available in the market that could be experimented further for the geartrain. The scissors gear could be used for the camshaft in Volvo engines to abate the commencement of rattling. It can be an interesting to investigate the auxiliaries which produce rattle and implement scissors gear or any other available technology on them. It could also be useful to have a pre-study and research on the gear coatings available to reduce noise and to ensure smother operation.

Utilization of a common rail direct injection (CRDI) system could have a drastic impact on the layout, noise and cost of the geartrain. Usage of CRDI systems eliminates the opposite torque from the camshafts. As a result of that the gears would be subjected to lower loads and hence appropriate materials alternate to steel can be experimented. Moreover, with CRDI systems there would be less torque irregularities across the geartrain and possibilities of considering scissors gears only for rattle producing auxiliary devices can be thought. The bevel gear system and the elliptic mechanism could be analyzed without considering the affects of opposite torque, which could simplify the development process. It can also be a good idea to study these concepts for a CRDI system.

As described in the above paragraphs there is a wide scope for improvement and further research of the geartrain from many aspects. There is also a potential to abate the noise produced from the gear rattle and internal vibrations that can be exploited. The future geartrains for the Volvo engines can nurture from the ideas and recommendation proposed in the thesis work to be the best amidst the present competitive market.

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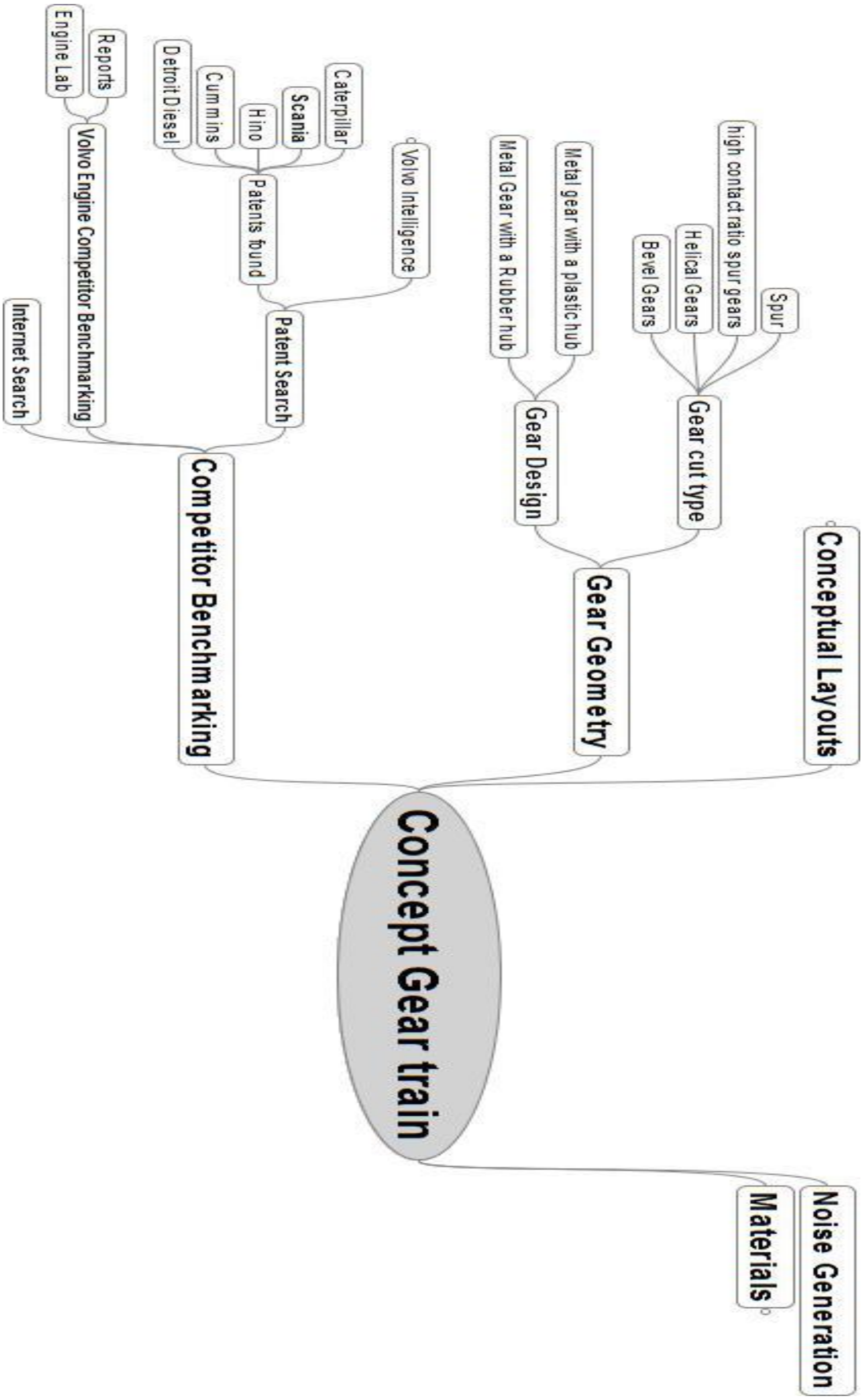
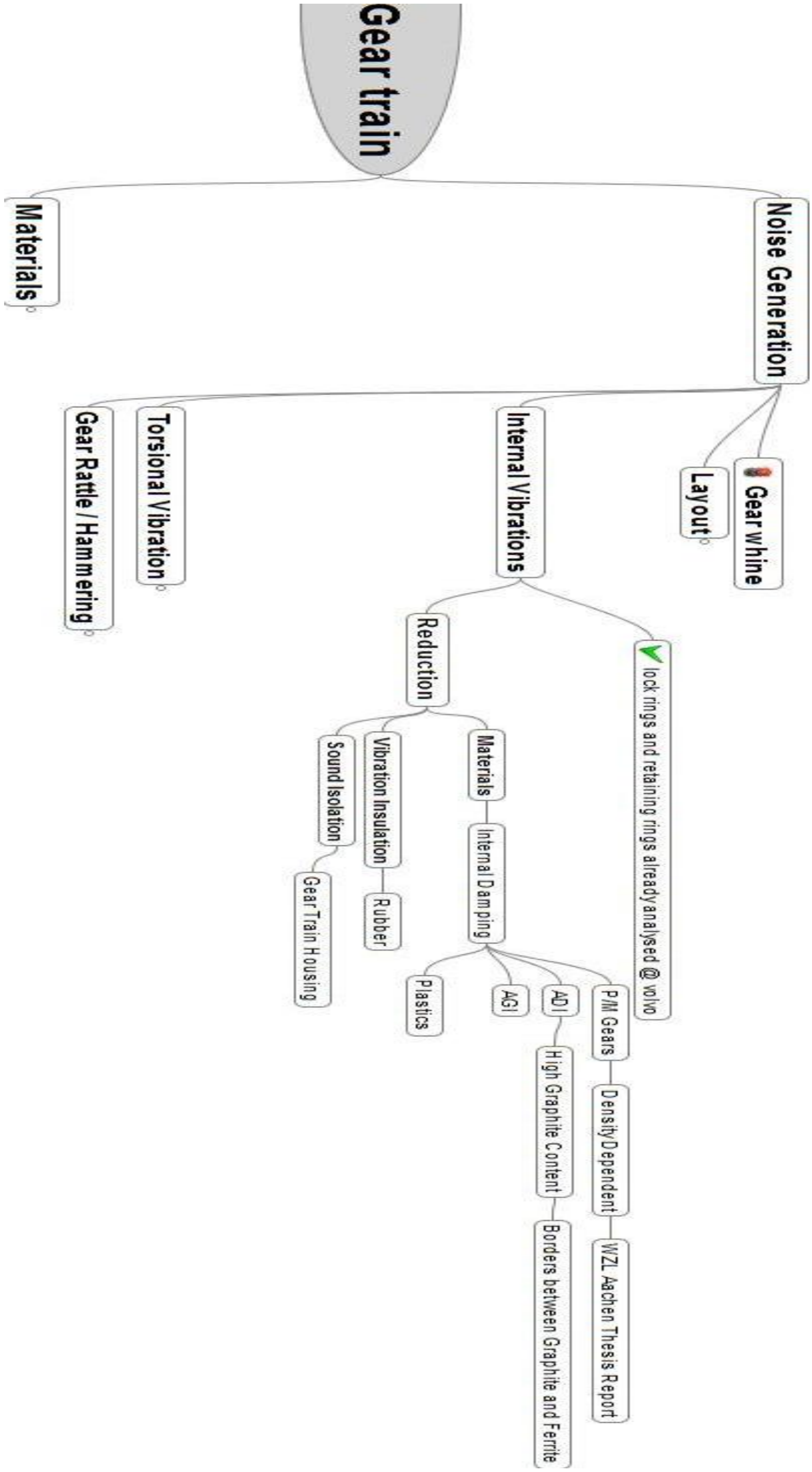
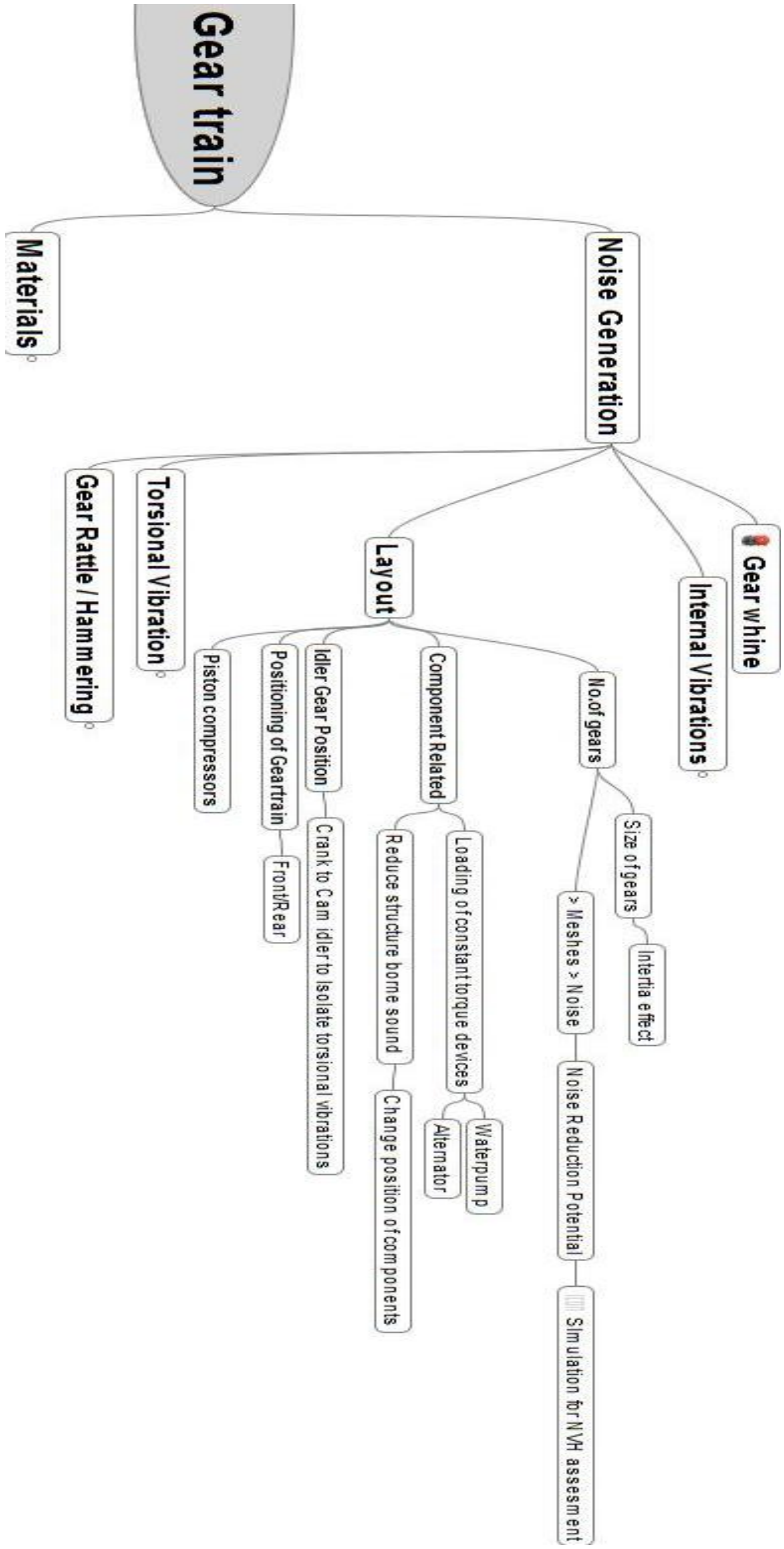
Appendix 1.1 Gear geometry and competitor benchmarking mind map



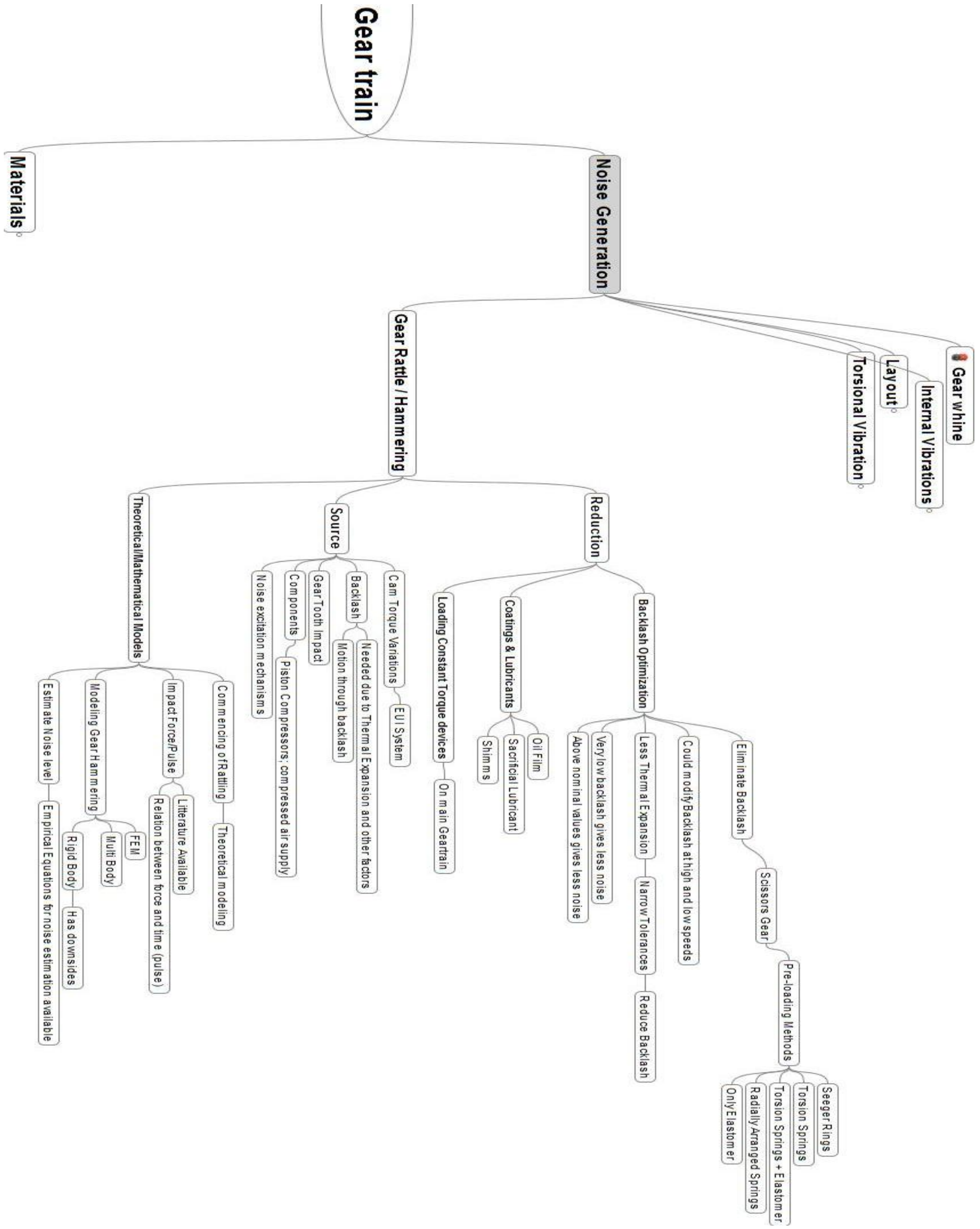
Appendix 1.2 Internal vibrations mind map



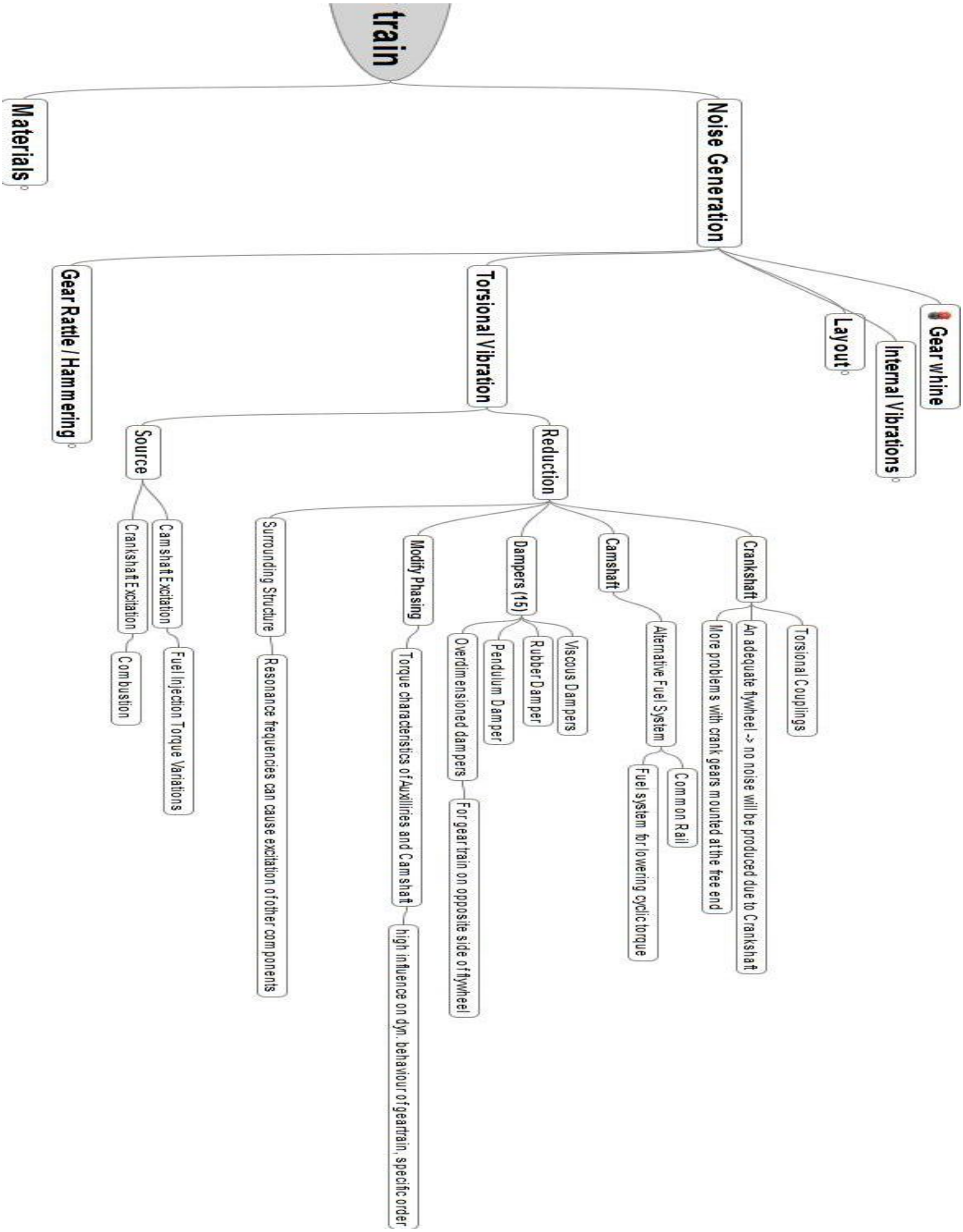
Appendix 1.3 Layout mind map



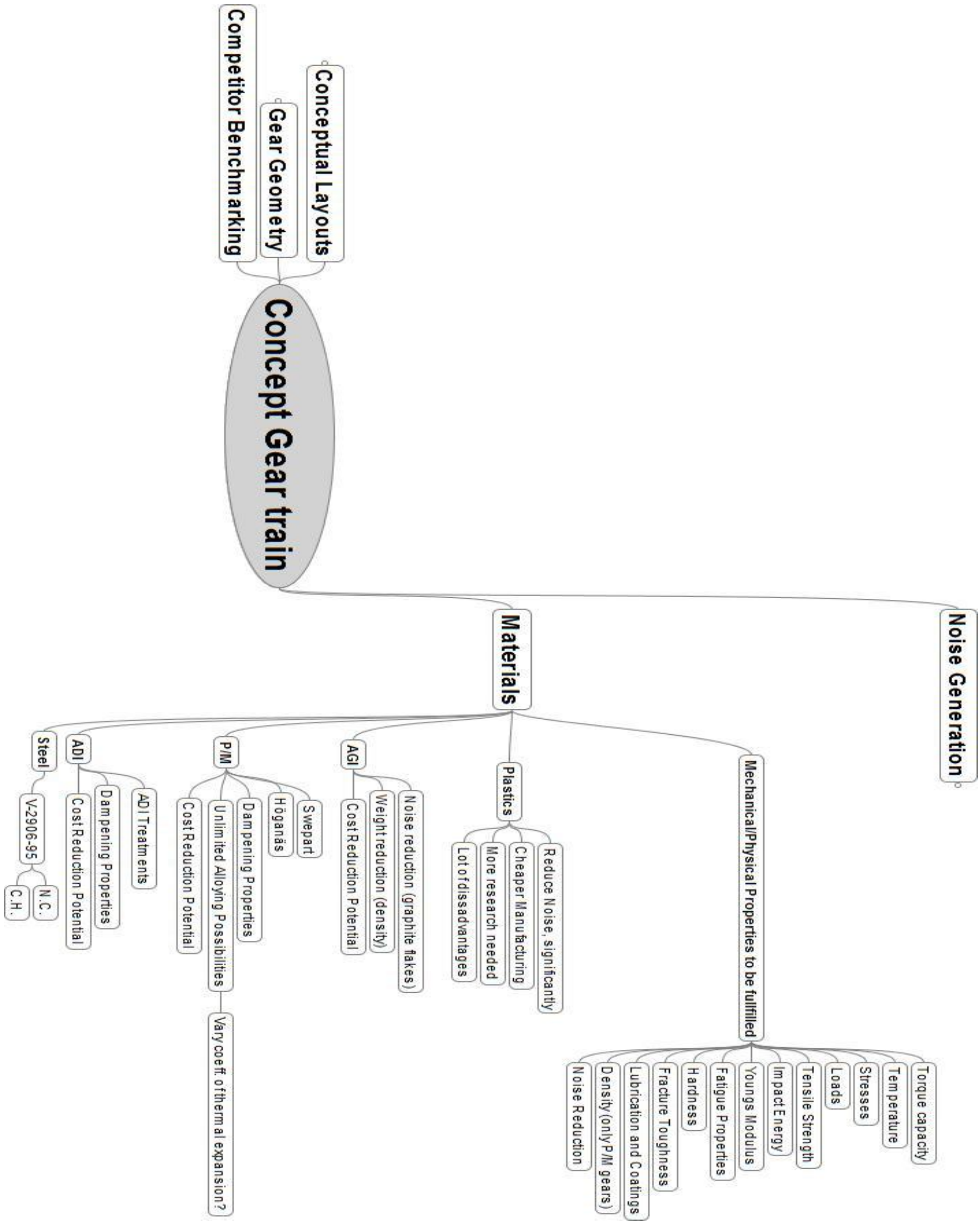
Appendix 1.4 Noise generation mind map



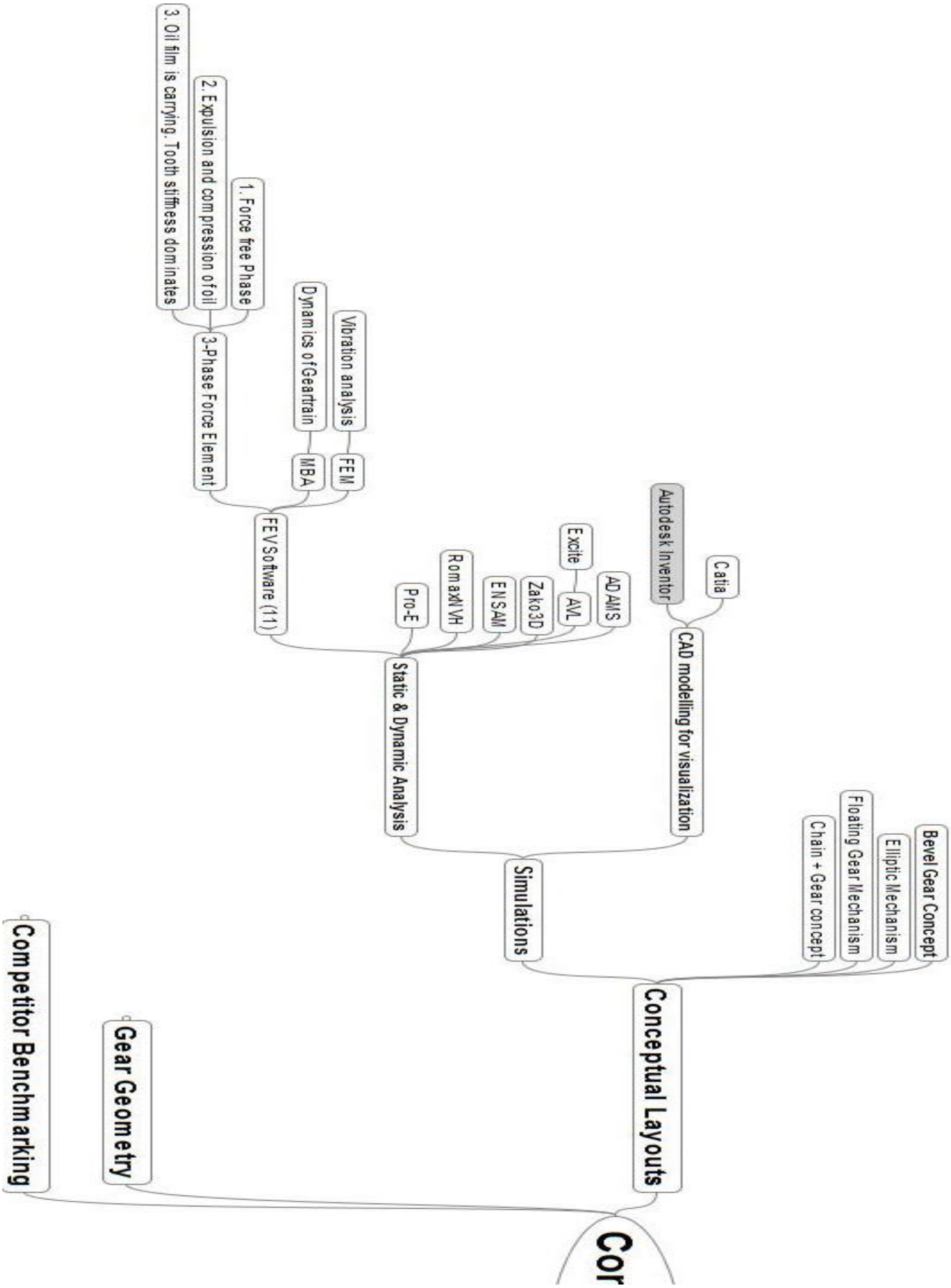
Appendix 1.5 Torsional vibrations mind map



Appendix 1.6 Materials mind map



Appendix 1.7 Conceptual layouts mind map



Appendix 2 Benchmarking Table

Competitor Benchmarking	Timing System / Cam Drive	Type of gears/chains /belts	Layout Solutions (Insert picture)	# Meshes between Crank and Cam	Timing Gear Position	Solutions for (rattle) noise reduction	Material	Injection System	Damper, Crank Shaft	Damper, Cam Shaft	Patents (gear noise reduction)
Volvo	Timing Gears / S.O.H.C	Helical gears. Helix angles varied.	Appendix 3.1	4	Rear		Nitro Carburized Steel and Case hardened steel	MEUI	Viscous Damper	Viscous Damper	
Competitors											
Scania R420 E5 (2008)	Timing Gears / S.O.H.C	Helical gears.	Appendix 3.2	3	Rear		Steel	MEUI - HPI system (Developed with Cummins)	Viscous Damper		Swedish Patent 0400686-2
Scania EURO 6								Common Rail (1800 bar)			
MAN D20	Timing Gears / S.O.H.C		Appendix 3.3	3	Rear (D20 Eng.)	(D20 Eng.) Scissors gear for for accessory drive	Steel	Common Rail	Vibration Damper (D20 Eng.)	No(D20 Eng.)	
Mercedes (Same as det DD15)											
Detroit Diesel Corp. DD15	Timing Gears / O.H.C	Mix of helical and spur gears	Appendix 3.4		Rear			Common Rail (900 bar)	Viscous Damper	No	
Cummins (ISB Engine)	Timing Gears / S.O.H.C	Spur Gears	N/A		Front	N/A		Common Rail (1800 bar)	Viscous Damper	No	
Cummins (ISX Engine)	Timing Gears / O.H.C	Spur Gears	Appendix 3.5		Front	The 600 HP version uses dual scissors gears for the Injector Cam Gear and one Idler.		UI	Viscous Damper		United States Patent US5979259
Caterpillar C13/ C15	Timing Gears / S.O.H.C	Spur Gears	Appendix 3.6	4	Front			MEUI	Viscous Damper	Roller/Pendulum Vibration Damper	United States Patent US7658124
Hino Motors	Timing Gears / Pushrod System		Appendix 3.7	1							1) JP2007071366A 2) JP2010133483A

Appendix 3.1 Volvo Geartrain Layout

Figure A.0.1: Volvo D13 Timing Geartrain

Appendix 3.2 Scania R420

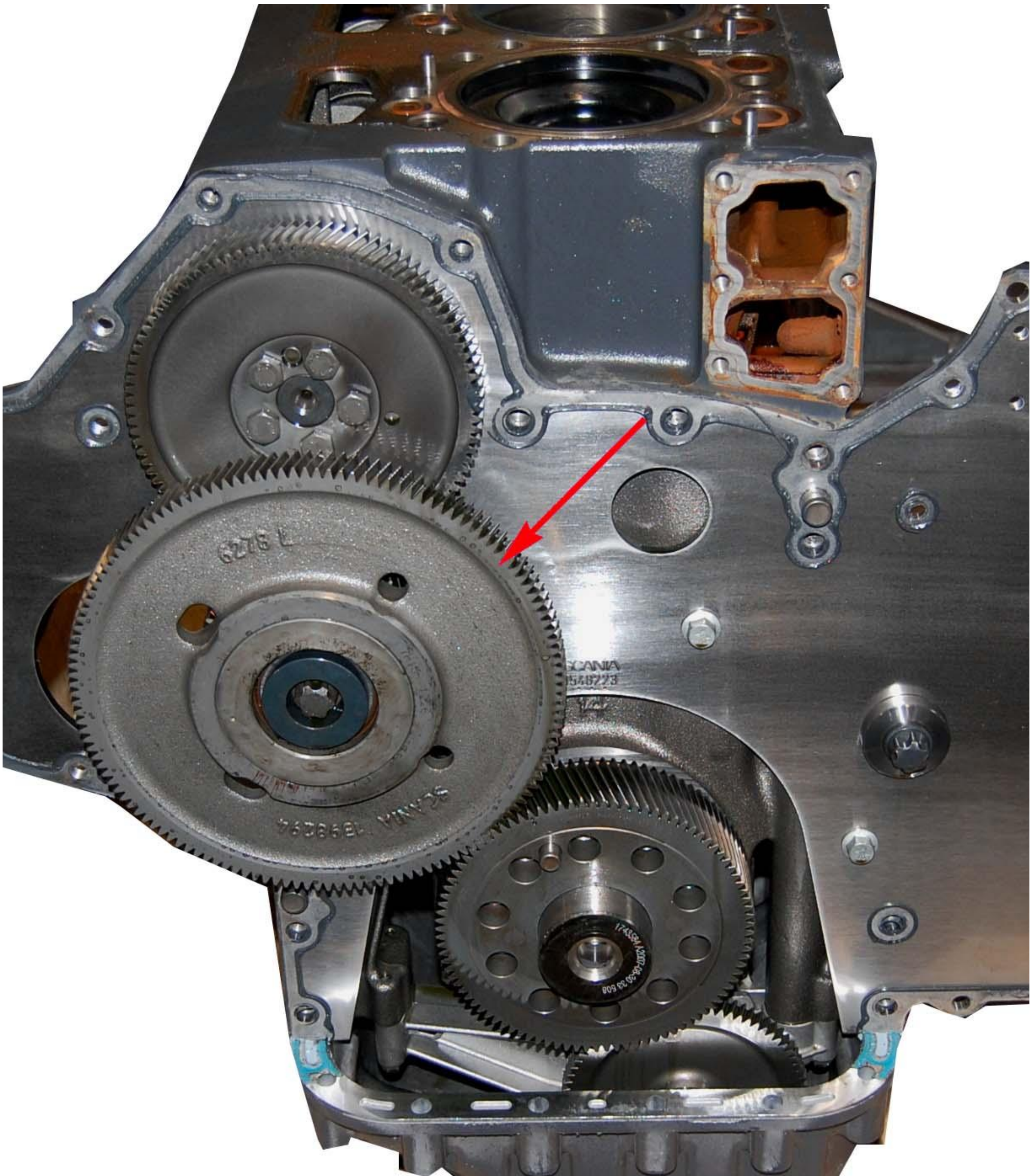


Figure A.0.1: Scania R420 Euro5 Geartrain [91]

Appendix 3.3 MAN D20

Figure A.0.1: MAN TGX 480 Euro4 D20 Engine geartrain layout [91]

Appendix 3.4 Detroit Diesel DD15

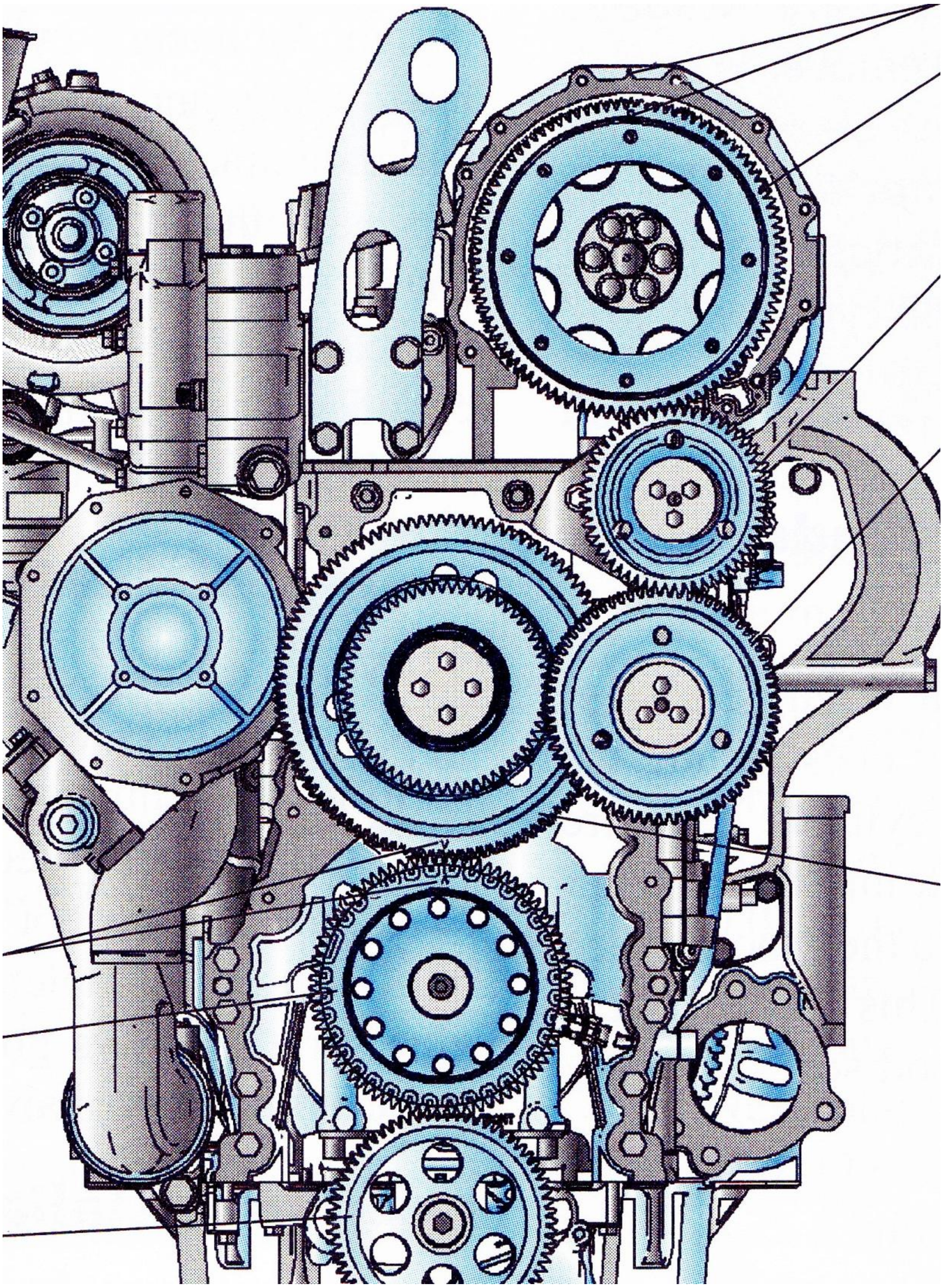


Figure A.0.1: Detroit Diesel, DD15 Engine geartrain layout [1]

Appendix 3.5 Cummins ISX

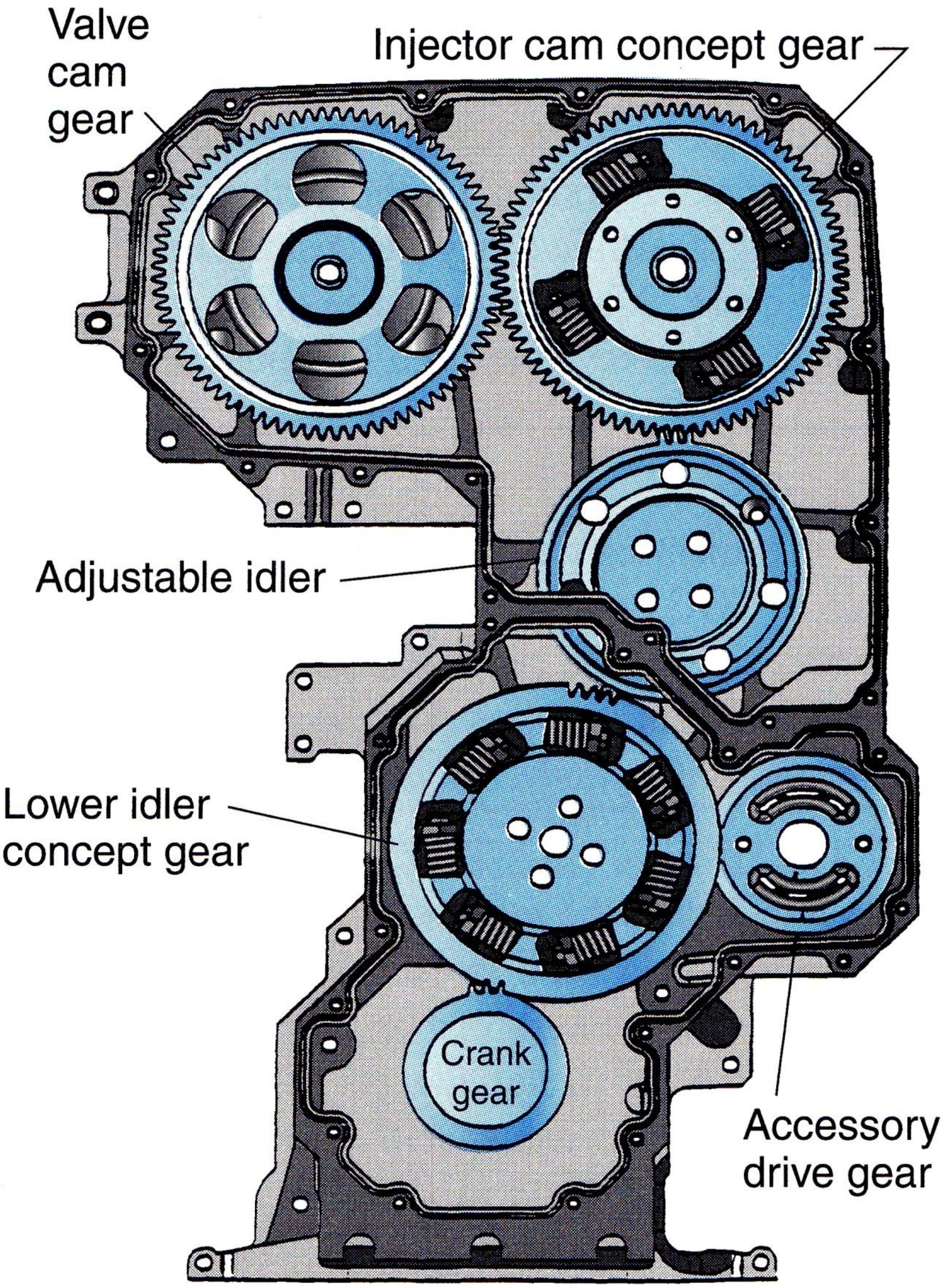


Figure 0.2: Cummins ISX Engine geartrain layout [1]

Appendix 3.6 Caterpillar C13

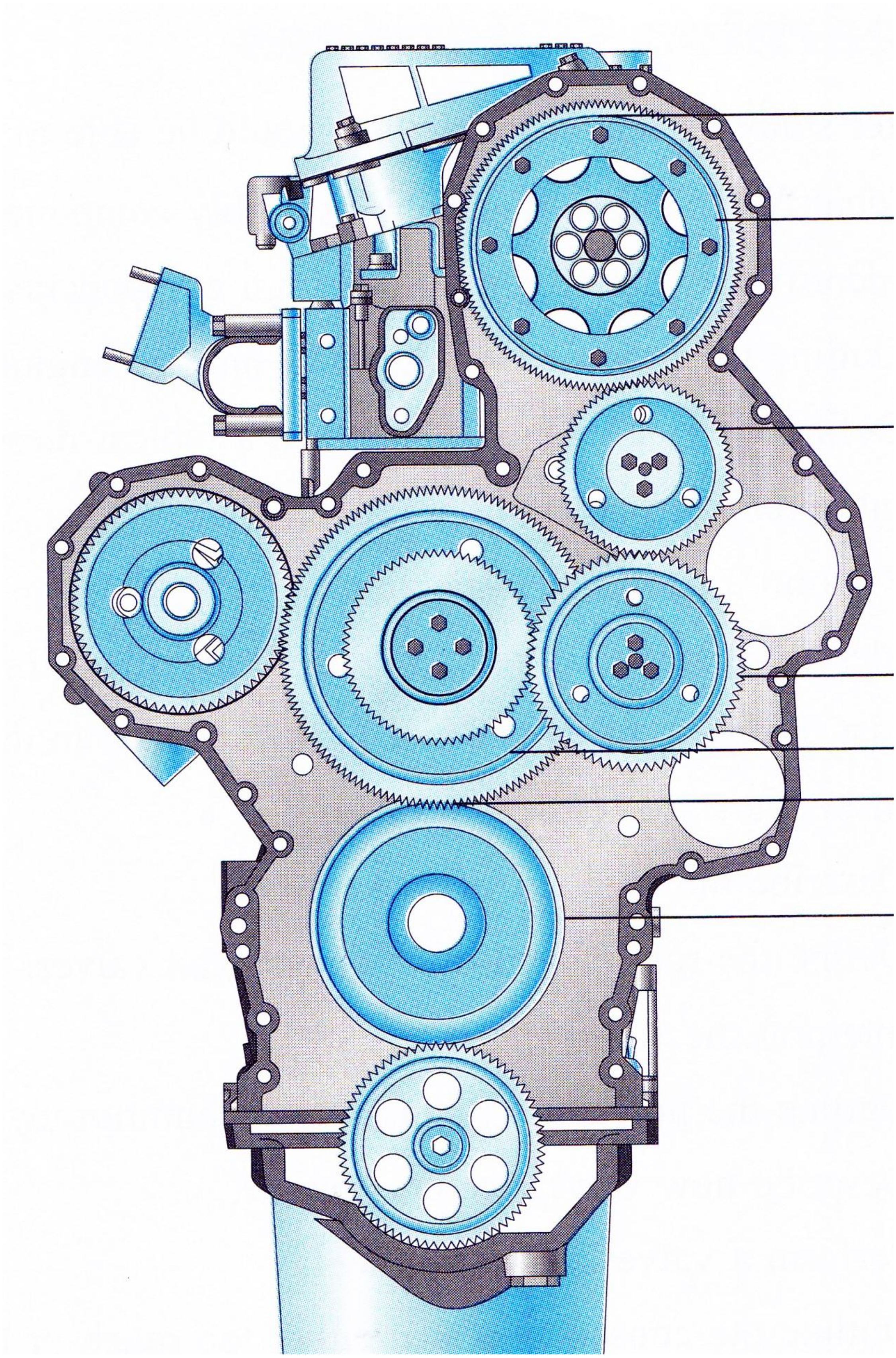


Figure 0.3: Caterpillar C13 Engine geartrain layout [1]

Appendix 3.7 Hino Motors V8

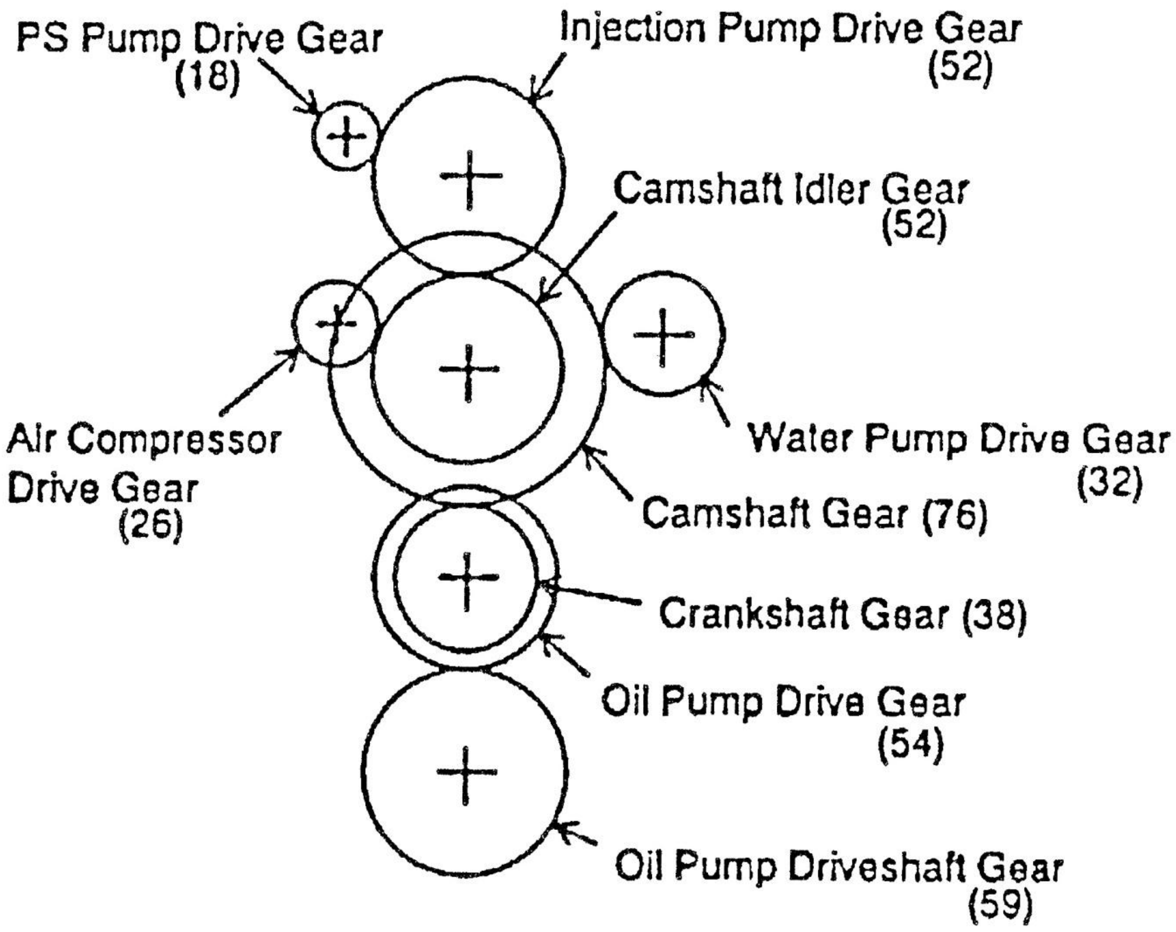


Figure 0.4: Hino Motors 20L V8 [76]