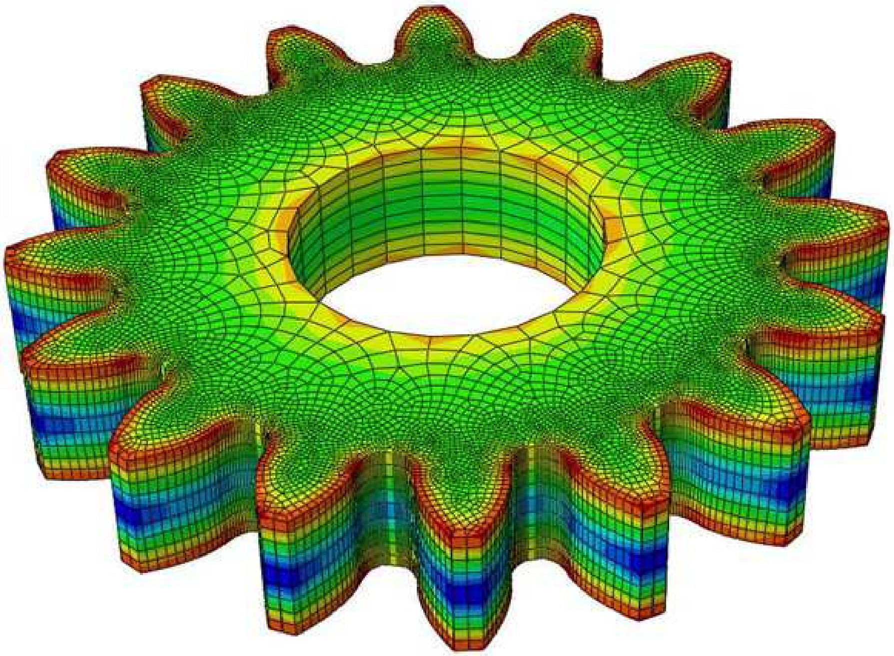
Innovative powder based manufacturing of gear wheels with high performance (HIPGEAR)

(Innovativ pulverbaserad tillverkning av kugghjul med höga prestanda)

Public report



Project within FFI
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Content

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Currently there are five collaboration programs**:** Electronics, Software and Communication, Energy and Environment, Traffic Safety and Automated Vehicles, Sustainable Production, Efficient and Connected Transport systems.

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1. Summary

The HIPGEAR project introduces an innovative manufacturing technology for gear wheels intended for heavy vehicle applications. The technology replaces conventional manufacturing steps such as hot forging, hobbing, broaching and turning with pressing of powder, sintering and Hot Isostatic Pressing (HIP). The new technology offers advantages in terms of less metal waste (up to 50% reduction) and less machining lubricant waste (up to 100% reduction). The specialized gear manufacturing technologies are replaced by general technologies which can be used for many types of manufacturing which adds flexibility to the production system.

A number of challenges were identified in order to reach fully dense gear wheels with the new technology. One of the most important ones was to avoid open porosity after pressing and sintering so that the HIPing process would be effective in closing all porosity. Three types of test object were used to check that all targets could be met. That includes test cylinders and two types of gear wheels with 32 and 84 mm dimeter. It was shown that metal alloys and processing routes could be found that generated fully dense gear wheels. The gear wheels will have a thin rim of pores on the surface which will have to be removed in finish grinding.

The properties were evaluated for the gear wheels with 84mm diameter. It was found that the flank pitting fatigue and the root bending fatigue strengths were within 10% of the strengths of reference gear wheels produced with conventional technologies.

The HIPGEAR project developed process planning tools based on the Finite Element Method which describe how the gear wheel develops during the new manufacturing steps. Factors such as geometry and porosity can be followed throughout the process chain. This is a powerful tool for process planning e.g. of pressing tools.

It was concluded that the technical targets of the project were reached and that it contributes to fulfilling environmental flexibility targets of FFI Sustainable production.

2. Sammanfattning på svenska

HIPGEAR projektet introducerar en innovative metod att tillverka kugghjul för användning i tunga fordon som lastbilar, bussar och entreprenadfordon. I den nya tekniken ersätts konventionell tillverkning baserad på varmsmide, svarvning, hobbning eller brotschning med pulvermetallurgisk tillverkning med pressning, sintring och Het Isostatisk Pressning (HIP). Den nya teknologin har fördelar genom att materialspillet reduceras med upp till 50% och genom att hantering av skärvätskor kan reduceras upp till 100%. I konventionell tillverkning används många starkt specialiserade

tillverkningstekniker medan den nya teknologin bygger på generella metoder som pressning och värmebehandling. Detta skapar nya möjligheter för en mer flexibel produktion.

I HIPGEAR projektet identifierades ett antal utmaningar i den nya teknologin och lösningar kunde skapas. En grundläggande problematik är att tekniken för att vara ekonomiskt konkurrenskraftig kräver att HIPning utförs på kugghjul utan yttre hölje. Att använda yttre behållare för varje komponent vid HIPning är annars en vanlig teknik för många dyrare komponenter. I kugghjulsfallet måste en gastät yta på kugghjulen åstadkommas på annat sätt. I HIPGEAR skedde detta genom att hjulen pressades och sintrades till så hög täthet att s.k. öppen porositet försvann. Nyckeln till att lyckas med detta ligger i materialval i puler, val av smörjmedel i pulvret, pulverstorlek, presstryck och sintringssekvens och temperatur. När den öppna porositeten är borta finns inga vägar för gasen i HIP utrustningen att nå kugghjulens inre och trycket i HIPen kan åstadkomma ett fullt tätt kugghjul. Den enda porositeten som återstår är i en tunn ytzon. Djupet på denna zon är ungefär av storleken hos ett pulverkorn dvs cirka 100mikrometer. Denna ytporositet måste avlägsnas i en avslutande slipningsoperation på de färdiga hjulen. Den nya tekniken utprovades på cylindrar, små kugghjul med diameter 32mm och på ett större kugghjul med diameter 84mm.

I HIPGEAR testades mekaniska egenskaper på de större tillverkade kugghjulen med 84mm diameter. Vid användning av kugghjul är i allmänhet utmattningsegenskaper avgörande. I projektet fann man att kuggflankens motstånd mot pittingskada och kuggrotens böjutmattningshållfasthet låg inom 10% från värden för konventionellt tillverkade kugghjul med samma geometri.

Tillverkningsprocessen i HIPGEAR innehåller helt nya tillverkningssteg jämfört med konventionell tillverkning. Det är viktigt att processplaneringsverktyg tas fram för de nya stegen så processplanering kan ske effektivt. Ett särskilt kritiskt steg är geometrival i presstegen. I HIPGEAR utvecklades en FEM baserad teknik som beskriver hur porositet och geometrier utvecklas i kugghjul under hela HIPGEAR processen. Med en sådan teknik kan man tex se hur olika val av pressgeometrier påverkar kugghjulets geometri efter HIP och speciellt dess avvikelse från nominella dimensioner så att man kan planera för den slutliga slipoperationen.

Slutsatsen av HIPGEAR är att de tekniska målen kunde nås och att dessa kan bidra till flera av FFIs övergripande mål med avseende på livscykeleffektivitet, konkurrenskraft, miljövänlighet, kvalitet och flexibilitet.

3. Background

Requirements for higher energy efficiency, lower emissions and higher load capacities put new demands on all parts of drive trains of heavy vehicles. This project specially addresses the transmissions. These must in the future sustain higher engine outputs at the same time as they are reduced in size and weight. This means that all present limitations of the transmission components must be addressed. The performance and life of gear wheels are today limited by inhomogenieties and defects in the material and from the manufacturing process. Examples of such limitations are:

- Uneven microstructure such as segregations
- Uneven and unfavorable distribution of larger inclusions
- Surface oxidation due to unfavorable steel composition
- Uneven residual stresses and distortions from heat treatments

These limitations to a large extent originate from disadvantages of conventional steel production and following manufacturing processes such as hot forging. Many of these disadvantages can be addressed by instead using powder metallurgy. Sinter steel technology is the most cost effective powder technology. However until now there have been a number of factors which have made the utilization of powder metallurgy difficult for high performance gear wheels:

- In sinter steel technology the gear wheels usually do not get fully dense after the manufacturing process. This means that fatigue properties are reduced compared to the fully dense state and thus has difficulties to compete with the performance of conventional steels.
- Some ways are available to increase the density but they are associated with significant cost. One example is to contain each gear wheel in a steel container and apply hot isostatic pressing (HIP). This is an expensive process.

Still if the mentioned disadvantages of powder metallurgy can be overcome a number of positive effects can be expected:

- The sinter steel technology is resource efficient since the waste material is much lower than for conventional production. Up to 50% of the material can be removed up to the final gear wheel for some applications but only few percent are lost in powder technology.
- The alloy composition in the sinter steels can be selected more freely than in conventional steel production. This can be used to increase performance and eliminate negative effects in manufacturing.
- One of the most important advantages of the powder materials are that they are highly homogeneous which will reduce problems with nonhomogeneous distortions and residual stresses.

In this project we have suggested and evaluated an innovative cost efficient process route to obtain fully dense gear wheels with sinter steel technology. The new technology is based on the following:

- The different alloying techniques from PM can be applied, which allows a great freedom in alloy composition.
- The powder is cold pressed to a shape which is very close to the final gear geometry. This technology can be applied to cylindrical and helical gear wheels.
- After the pressing stages the material is sintered to such a condition that the surface of the gear wheel becomes gas tight.
- The gear wheels can then be loaded in large batches into HIP furnaces to obtain the final fully dense state. No separate gas tight containers are needed around each gear wheel since the surface of the gear wheels is already sufficiently gas tight.
- After HIPing the gear wheels are carburized and finished in a similar way as for conventionally produced materials.

To our knowledge this approach is unique to the heavy vehicle industry both at the start and finish of the project. It is based on the world leading powder metallurgy competence in Sweden with leading producers of sinter steels and HIP furnaces.

The project evaluated the new innovations of the project and how well the ideas could be realized and target properties could be reached.

4. Purpose, research questions and method

The purpose of the HIPGEAR project is to suggest and evaluate a new environmentally friendly cost efficient technology for production of gear wheels for heavy vehicles with a potential to give gears with better product properties than with today´s technology.

HIPGEAR suggests an innovative manufacturing technology for gear wheels. It replaces manufacturing based on conventionally produced bar steels with powder metallurgical materials. The main limitation of present sinter steel technologies is that the materials are not fully dense in the final state. This problem is overcome by a tailored combination of pressing/sintering and HIPing technologies.

A number of research questions linked to the new technology were formulated:

- Is it possible to find alloy compositions of the sinter steels which are appropriate for gear wheel applications for heavy vehicles.
- What size and shape limitations exist for the production of gear wheels for heavy vehicles with the new technology.
- How shall the pressing/sintering be performed in order to get a gas tight gear surface appropriate for subsequent HIPing.
- How do the new gear wheels respond to carburizing
- What finishing operations are needed after HIPing.

- Is it possible to formulate process planning tools for the new process steps
- What performance levels can be expected for gears with the new technology

A large number of experimental and simulation techniques were used to answer the research questions. Simulation tools were developed for the new process chain to predict densities and distortions in the final gear wheels. These simulations were based on FEM. They were verified by experimental trials and were used to show how different gear wheel geometries respond to the new technology. A number of sinter steel variants were produced and their behaviour in the process chain were evaluated with respect to microstructures and densities. A number of test objects were used for trials namely test cylinders, small and large (FZG) gear wheels. Carburizing and grinding was evaluated for the gear wheels. Finally fatigue properties were evaluated for the FZG gear wheels and compared to reference data for conventionally produced gear wheels.

5. Objective

The objectives of the project were formulated in the following way in the proposal:

The project has a direct link to FFI´s overall objectives in the following way:

- In the project an initiative is taken to leverage with the world leading Swedish Powder Metallurgical industry within a new area namely transmissions for heavy vehicles. Both Höganäs and Quintus Technology are internationally leading in their areas. This implies a new combination of research and innovation capacity in the industrial area of heavy vehicles.
- The project builds on cooperation between material, equipment provider, component subcontractor and OEMs of different sizes.
- The project means a new combination of vehicle and powder metallurgical industries.
- In the project companies cooperate with research institutes and universities.

The project is closely linked to the road map for Sustainable production within FFI for 2020 as was available 2013 when this proposal was formulated.

- Environmental goals are met through reduction of waste of raw materials
- Cost efficiency is achieved by reduction of waste in raw materials through the new powder technology
- New material and process solutions are suggested to achieve higher performance and thus reduced weight of transmissions.
- Virtual methods are developed for process planning of the new process chain.

A new version of the Road Map of FFI Sustainable production was formulated in 2016 and aims for the time period up to 2030. Although this was generated after the proposal of HIPGEAR we will relate to it here. The new Road Map identifies 6 primary Program areas of which 5 are closely related to HIPGEAR:

- New product with high life cycle efficiency. HIPGEAR introduces new materials and manufacturing processes for gear wheels. The new technology is favorable from the life cycle perspective since it will generate much less metallic and processing waste during production.
- Competitiveness. The powder metallurgy manufacturing route with its high resource efficiency is highly cost effective especially for large production series and in that way contributes to high competitiveness.
- Environment. The elimination of steel waste and lubricant waste from maching will significantly reduce environmental impact.
- Quality. HIPGEAR provides a simulation tool which describes how gear shapes develop during the entire manufacturing process chain. This can be an important tool to analyse and trace back quality sources.
- Flexibility. Gear production is today based on a chain of highly specialized manufacturing equipment such as hobbing equipment and broaches. The specialization of the equipment limits flexibility. The powder manufacturing route suggested in HIPGEAR is based on widely applicable equipment such as mechanical presses, heat treatment furnaces and HIPing equipment. This opens up for a more flexible production of gear wheels.

Finally in this chapter we review the overall objectives of the project:

- 30% lower material consumption by replacement of today´s chip removing machining operations with the new powder technology with only small material losses.

  Up to 50% of the material has to be removed in machining for some gear wheel geometries in conventional production. In powder based production these losses are only a few percent. So the objective is achieved.

- 40% higher productivity in process planning.

  With the new technology process planning for gear turning and milling is discarded and replaced by process planning for pressing tools, sintering processes and HIP. In the project a new process planning tool was developed based on FEM. It has good potential for high productivity but we could not measure exactly how much it contributes to productivity compared to conventional production.

6. Results and deliverables

6.1 The HIPGEAR process chain and its challenges

In the HIPGEAR process entirely new process steps for gear manufacturing are replacing the conventional steps from steel manufacturing up to the very final stages of heat treatment and finishing. The last stages are similar in the conventional and new process chains. This is illustrated in Fig 1 which describes the steps of the new process as :

- Die filling where the tooling designed for the powder pressing is filled with powder
- Powder pressing where the mechanical press compacts the powder to the die shape. It is essentially during the pressing operation that the density of the gear wheel is determined.
- Sintering. The pressing and sintering operations can be performed in one or in two rounds. Often two rounds are required to reach a desired density levels.
- HIPing under Argon gas at a high pressure and temperature so that remaining pores in the gear wheels are closed. This operation should give a fully dense gear wheel.
- A carburizing treatment is applied to obtain the specified hardness distribution of the gear wheels. This is the same type of operation in conventional and HIPGEAR processing although adoption must be done to the specific steel alloy used.
- A finishing operation is applied to meet geometrical specifications of the gear wheel. The amount of removed material can of course be different after the HIPGEAR process and in conventional production.

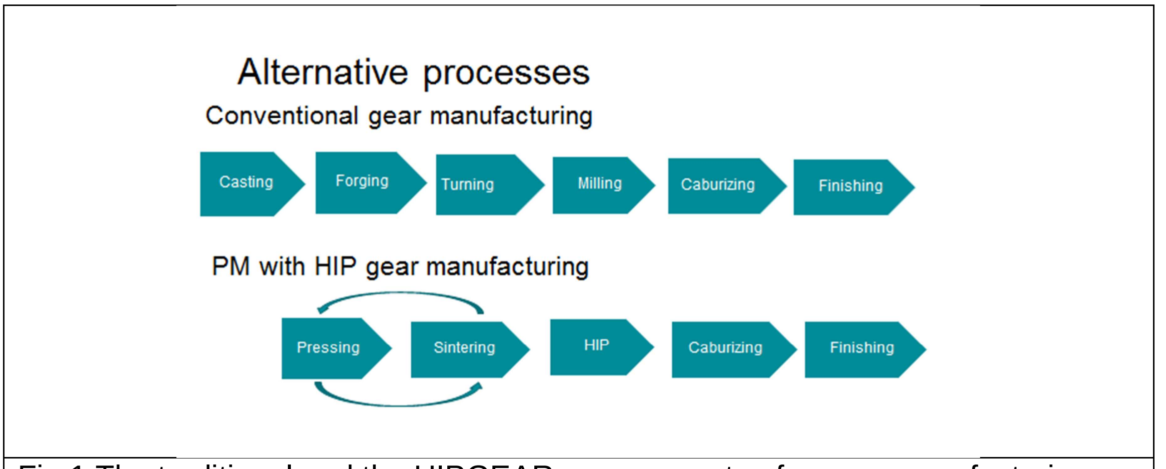

Fig 1 The traditional and the HIPGEAR process routes for gear manufacturing

The main challenges and limitations of the new process route are:

- The gear wheels will be HIPed without individual containers. This means that the surface of the sintered wheels must be gas tight since the pressure in a HIP is introduced via gas. The sintered gear wheels are gas tight if open porosity can be avoided. This can be achieved if the porosity after pressing is kept below a certain level, usually between 5-10%. The main difficulty to achieve this is in the so called dead zone of the sintered gear wheel. In the dead zone the deformations are smaller during pressing so the porosity becomes relatively larger than in other parts of the pressed object. It occurs in the middle height of the gear wheels in the so called neutral zone.

- Porosity of similar depth as a powder grain size will always occur in the processed gear wheels. This is due to fact that this porosity will always remain open up to the surface for simple geometrical reasons. This porosity must be removed by the finishing operation e.g. grinding.
- Some process steps are at rather high temperature or around 1200-1300C which means that grain sizes can become high. Actions must be taken to reduce this grain size to levels typical to the levels in conventional gear manufacturing.
- The capacity of the mechanical presses used in powder compaction limits the sizes of gear wheels which can be manufactured. As an example presses of the capacity of 800tons which in itself is rather large for sinter steel production sets a limit at gear wheels of outer diameter 120mm or wheels with the same cross section.
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6.2 Demonstrators and test objects

In the HIPGEAR project the challenges were addressed by developing and optimizing the material and process conditions. This was done both based on experimental techniques and simulation. The tests were made on a number of different demonstrators which are illustrated in Fig 2. Many trials were made on test cylinders with a dimeter of 20mm and a height of 25mm. As a first hand demonstrator we used a small gear wheel with a dimeter of 32mm. As final demonstrator we used a so called FZG geometry with a dimeter of 84mm. This geometry can also be subjected to standardized gear testing in test benches.

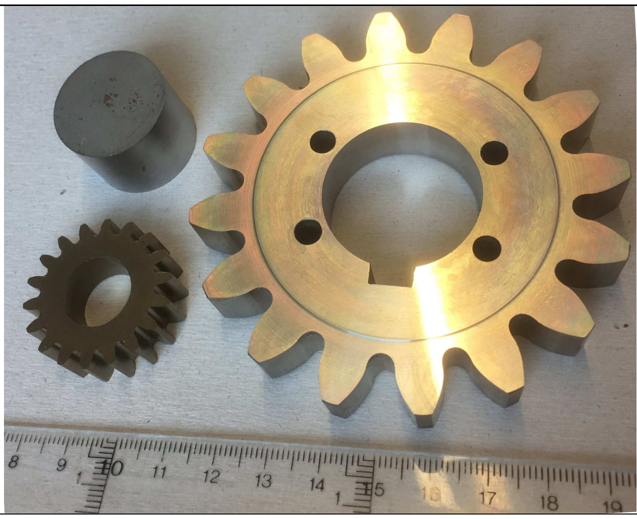

Fig 2 Test objects used I the project: Cylinder, Small gear wheel and FZG gear wheel.

6.3 Simulation of the HIPGEAR process chain

In the case of gear wheels many geometrical parameters influence the material response during processing with the HIPGEAR chain in a rather complex way. A Finite Element simulation model was developed to describe how local material density and distortions develop during processing.

- The die filling was described in a simple way by assuming that the resulting density was homogenous
- The first pressing was described with due consideration of material response and friction. The material was described with the CAP model.
- The only described effect of sintering was a density change.
- In the second pressing the material description was changed to the Gurson model.
- The second sintering was described in a similar way as the first one.
- HIPing was described by applying a surface pressure on the surfaces of the body.

During these simulations the development of geometry, density and flow stress can be followed locally in the tested gear wheels.

Fig 3 shows how the pressing model looks for the FZG gear wheel. The two punches move towards one another until the intended height is obtained.

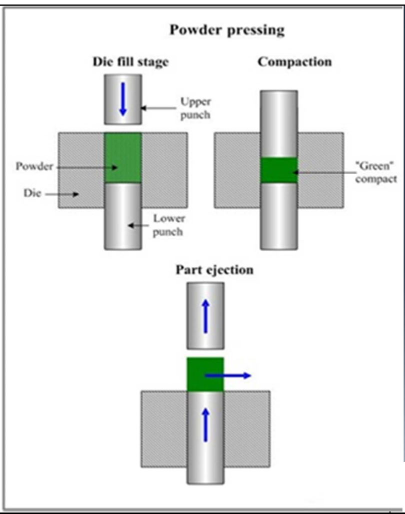

Fig 3a First pressing.

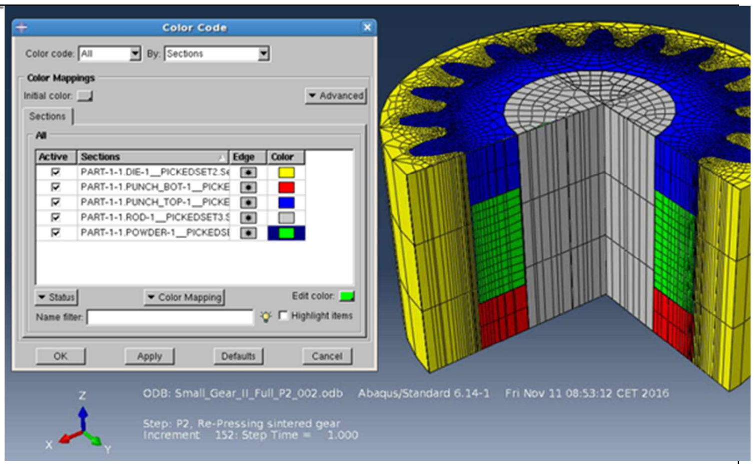

Fig 3b FE model of the first pressing of FZG gear wheel

The relative density after pressing and sintering is illustrated for the FZG gear wheel in Fig 4a. It can be seen that the lowest densities (Blue) are obtained in the mid section of the gear wheel, in the so called dead zone. In this particular case this minimum density is round 90% which is on the limit of avoiding open porosity. After the HIPing stage, Fig 4b, the density reaches close to 100% everywhere in the gear wheel.

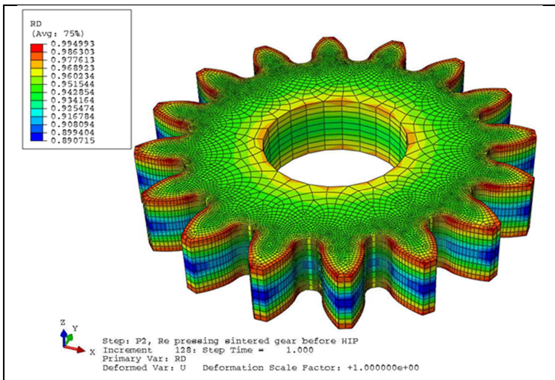

Fig 4 a. Relative density after the two pressings and sintering operations on FZG gear wheel.

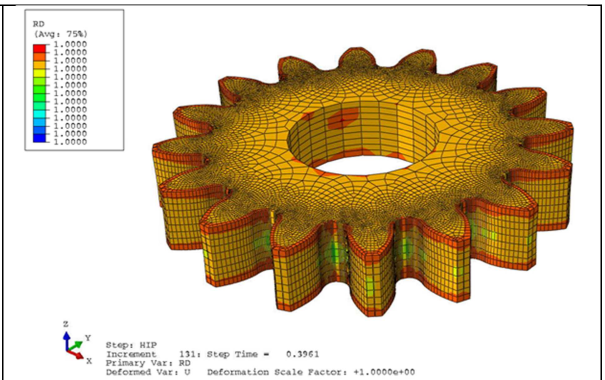

Fig 4b Relative density after HIPing.

During the second pressing the gear geometry will to a large extent fill out the die geometry. We simulate the sintering as a percentage reduction of density so the geometry will be little changed by sintering. However in the HIPing all local densities will approach 100% which means that the material will shrink the most in the middle region. A significant distortion will occur. The gear teeth will shrink in their mid sections. This is illustrated in Fig Fig5.

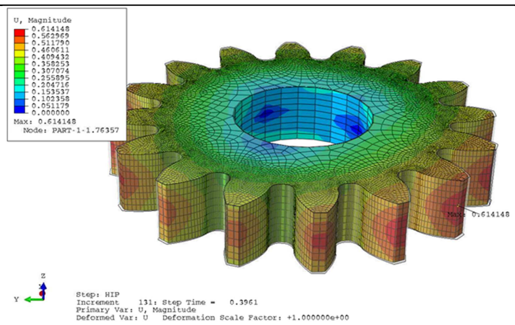

Fig 5 Distortion after HIPing

The FE model can be used by process design engineer to optimise the process chain.

The FE model can be used to follow densities and geometries during processing. In the project we used it to show how different gear wheel parameters like diameter, modulus, number of teeth and width influence the tendency to form a dead zone with low density after pressing and sintering. It was shown that some gear wheels will be more difficult to manufacture with this technology than others. One example of this was that we predicted that the small gear wheel would be more difficult than the large FZG gear wheel. It also was found experimentally that it was more difficult to get fully dense small gear wheels than for the FZG wheels.

Another application of the FE simulation model is to predict what exact geometry the pressing tools should have to give a certain final geometry after HIP. This is important for tool design since many stages of non-homogeneous complex shrinkage occur in sintering and HIP.

6.4 Material and process development

In the HIPGEAR project the material and gear responses were studied during the process chain for the three testing objects. A number of different material and processing variants were tested:

- Astaloy™ Mo which contains 1.5%Mo
- Two different lubricants
- Two different carbon levels
- Two different powder size distributions
- Three different sintering temperatures
- Single or double pressing/sintering
- Two different carburing treatments

The material and process optimisation main challenge is to avoid open porosity which leads to low density after HIP and at the same time trying to avoid the above material and process variants which generate excessive cost. It was found that the standard powder size distribution was satisfactory to obtain a good result. This is good from the cost point of view. However it was not possible to avoid double sintering/pressing. The highest sintering temperatures usually give the best results regarding porosity but might require more expensive furnaces. It also has a tendency to generate very large grain sizes in the final condition which can be negative to properties. This effect can be eliminated by an extra normalizing heat treatment after HIP if required. But this of course adds cost.

Fig 6a illustrates the porosity after the second sintering which can eliminated in a successful HIP treatment as in Fig 6b.

Fig 7a gives one example of how the pore distribution can look like after HIP if the pore contents is too high after second sintering. Fig 7b shows a case where the open porosity was reduced by reducing the pore contents after second sintering compared to Fig 7a. Fig8 shows a successful case with no porosity after HIP.

As was mentioned previously some pore content will always be present at the surface after HIP. It will extend some powder grain size into the material. An example of this is given in Fig 9. This porosity must be removed in the final finishing e.g. grinding operation.

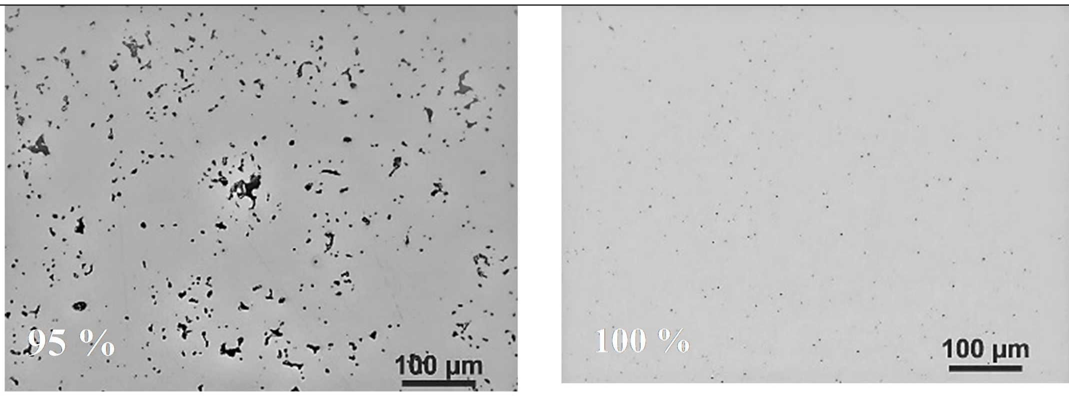

Fig 6 Example of pore distribution before (a) and after HIP operation(b).

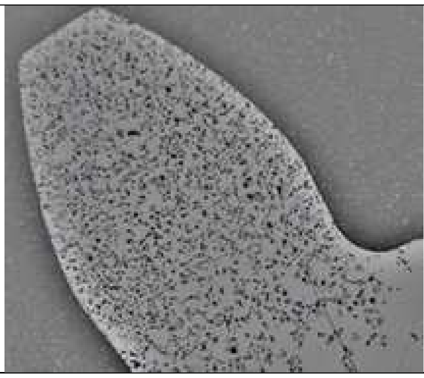

Fig 7a Example of pores after HIP with open porosity

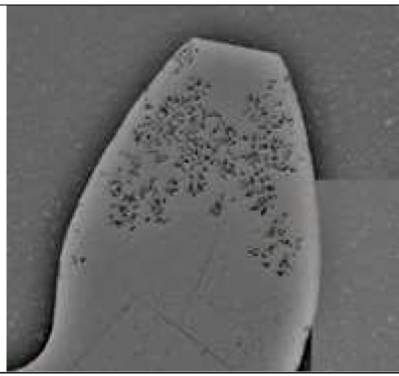

Fig 7b Examples of Partial open porosity after HIP

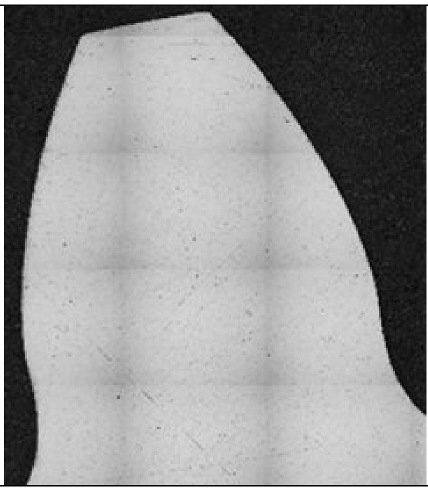	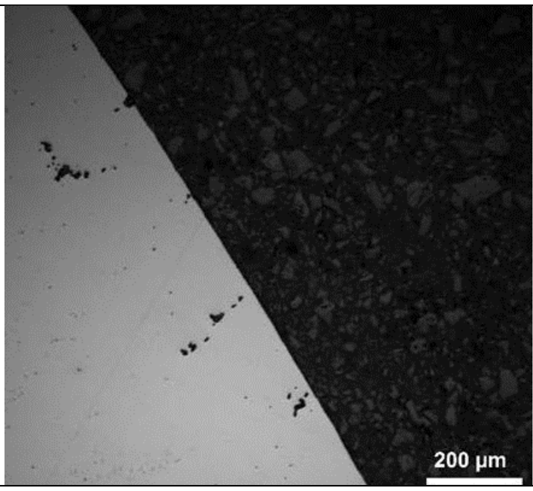
Fig 8 Fully closed pores after HIP	Fig 9 Surface pores after HIP

6.5 Gear properties after the HIPGEAR process

Two gear wheel properties were evaluated in the HIPGEAR project namely the flank pitting fatigue in FZG rig testing and gear tooth fatigue strength in tooth bending tests.

Fig 10 for the FZG pitting tests shows that the test results for the HIPGEAR FZG gear wheel are within the test results for a reference conventionally produced gear wheels.

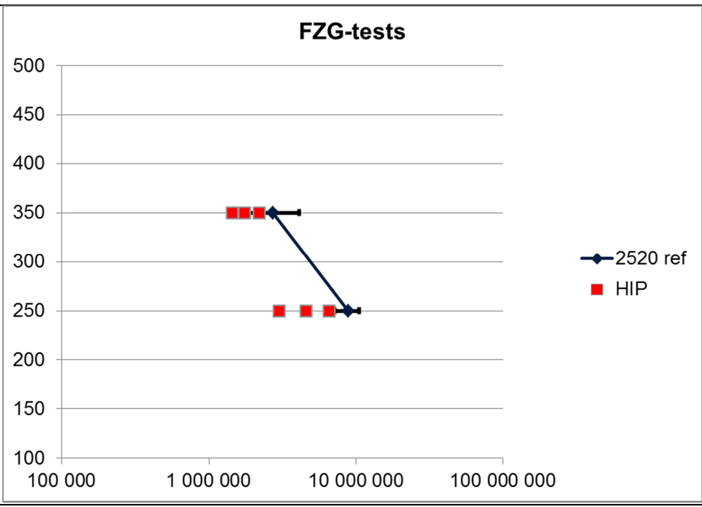

Fig 10 FZG rig test results for flank pitting fatigue.

The tooth root bending test results of Fig 11 show that HIPGEAR wheels give a bending fatigue strength which is within 10% of the results for conventionally produced gear wheels.

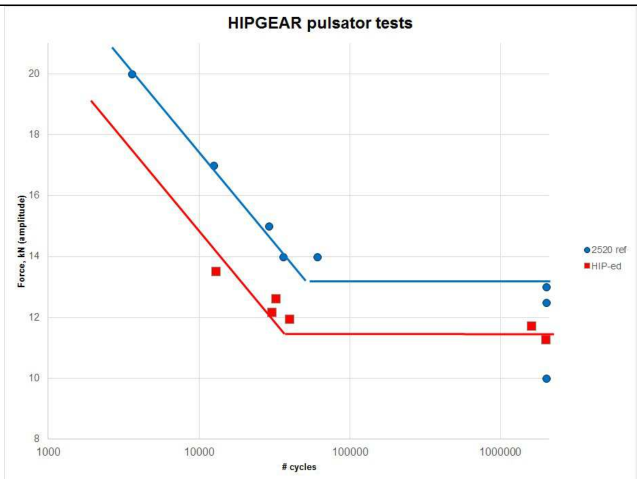

Fig 11 Tooth root bending fatigue tests.

6.6 Discussion of the results

As was mentioned at the beginning of this section a number of challenges had to be addressed in the HIPGEAR project. Solutions were found for most of them.

The new process chain of HIPGEAR with pressing, sintering and HIPing can be described with Finite Element Methods med good accuracy. This will be an efficient tool for process planning of pressing tool geometries.

The issues with open porosity which leads to remaining porosity after HIP can usually be solved by optimising material and process conditions. However some gear wheel geometries will be more difficult from this perspective than others. We have analysed how difficult different geometries will be.

A thin surface zone will contain pores after the process chain. It has to be eliminated in the finishing operation. The depth of the zone can be some 0.2mm which means that a similar grinding depth must be used.

The process chain contains high processing temperatures specially in sintering. This can lead to large grain sizes which can be negative to fatigue properties. The grain size can be brought back to normal size by a separate normalizing heat treatment or by a slightly elongated HIP cycle with integrated cooling and heating.

The fatigue results as for pitting and root bending fatigue are within 10% of the results for reference gear wheels produced with conventional technology. Coarse grain sizes which can occur after sintering at high temperature can reduce bending fatigue strength by some 10%.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	This is a new process chain and its opportunities must now be communicated to interested industries.
Be passed on to other advanced technological development projects	X	The next step is to show that the new technology will work for angular gear wheels (which are dominating today)
Be passed on to product development projects		Too early
Introduced on the market		Too early
Used in investigations / regulatory / licensing / political decisions		Can be relevant to prepare for future manufacturing techniques which are beneficial for environment.

During the project time dissemination of results was accomplished through

- project meetings (more than 40) with a number of different project teams,
- working group meetings,
- HIPGEAR final seminar,
- FFI seminars and
- International conferences

7.2 Publications

- Innovative powder based manufacturing of high performance gears, Alireza Khodaee, Maheswaran Vattur Sundaram , Michael Andersson, Arne Melander, Annika Strondl, Irma Heikkilä, Arthur Miedzinski, Lars Nyborg and Magnus Ahlfors, Publication in Conference World PM 2016 (Hamburg)
- Evaluation of Effects of Geometrical Parameters on Density Distribution in Compaction of PM Gears, Alireza Khodaee and Arne Melander, Publication in Conference ESAFORM 2016 (Dublin)
- Processing method to reach full density powder metallurgy gears, Maheswaran Vattur Sundaram, Alireza Khodaee, Michael Andersson, Lars Nyborg, Arne Melander, Submitted Int J Powder Metallurgy 2018
- Analysis on the gear size influences on the gear quality and strength in the manufacturing of PM Gears with an innovative powder processing route using FEM, Alireza Khodaee and Arne Melander , to be published 2018.

8. Conclusions and future research

A new power based technology was developed to manufacture fully dense gear wheels for heavy truck applications. The following conclusions were drawn:

- A new technology was developed with clear environmental benefits compared to conventional production in terms of reduced metal waste (up to 50% reduction) and reduced machining lubricant waste (100% reduction).
- The new manufacturing chain avoids specialized manufacturing equipment for gear wheels like hobbing or broaching and instead uses general equipment technologies like pressing, sintering and HIPing. This is favorable from the flexibility point of view.
- A new tool for process planning during the new HIPGEAR manufacturing chain was developed based on the Finite Element Method and was verified. This new tool can efficiently contribute to future process planning.
- Material optimization was performed which identified suitable material composition, powder grain sizes and lubricants.
- Process optimization identified pressing/sintering sequences and sintering temperatures required in the process.
- One major challenge is to get the gear wheels fully dense after the HIPing operation. It was found that it is important to maintain the relative density above a certain level everywhere in the gear wheels after pressing and sintering. In that way open porosity can be avoided and the wheels become fully dense after HIPing.
- The HIPGEAR process chain leads to a surface zone with porosity which has to be removed in the finishing operation.
- Two types of demonstrators were manufactured with the new technology, one small gear wheel with diameter 32 mm and one large gear wheel with dimeter 84mm.
- The largest gear wheel was tested as for fatigue properties and showed strengths within 10% of flank pitting fatigue and root bending fatigue properties as gear wheels produced with conventional technology.
- It was concluded that the targets of the project were reached.

Comments on future research: In the HIPGEAR project demonstrators were used with spur gears. In modern gear boxes the gear wheels are mostly of helical design. The next step in the development of the present technology is to demonstrate it for helical gear wheels. It can be expected that this will be more challenging than for the spur gears. The reason is that larger gradients in density can occur during pressing which means that methods must be developed to avoid open porosity also in that case. This will be the next stage in development. After such a successful stage it is expected that the technology is ready to be used in products.

9. Participating parties and contact persons

Logos	Project party	Contact person
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	Chalmers Tekniska Högskola	Lars Nyborg
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