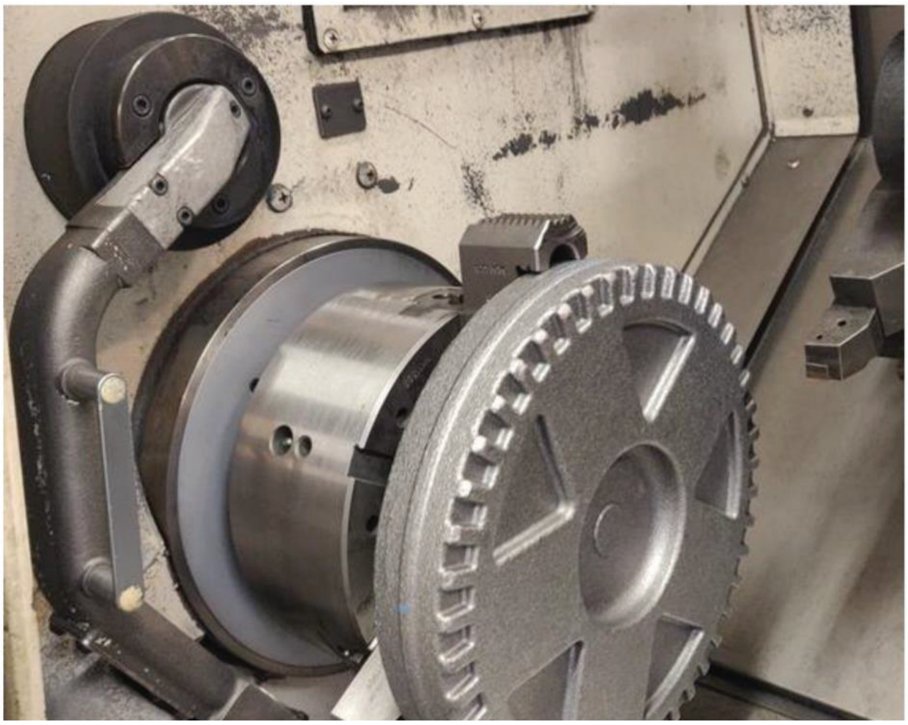
EcoGear - Miljövänlig produktion av koniska kugghjul genom användning av försmidda ämnen

Publik rapport



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Datum: 2023-09-01

Projekt inom Hållbar produktion

FFI Fordonsstrategisk Forskning och Innovation

Innehållsförteckning

1 Sammanfattning

Projektet har studerat bearbetning av smidda kugghjul med tandluckor för kuggbearbetning med ökad miljömässig hållbarhet. I projektet har påvisat att kronhjul smidda med tandluckor är möjligt att framställa både i smidesprocessen och vid bearbetning.
Bearbetningstester har genomförts både i testmiljö hos Kungliga Tekniska högskolan och Swerim samt i verklig industriell miljö i produktionsmaskiner på Scania. För att hela processkedjan med smidda ämnen ska fungera har ett referenssystem för fastspänning av kronhjul med tandluckor tagits fram inom projektet. Referenssystemet nyttjar mekanik för att säkerställa noggrannhet och repeterbarhet vid bearbetning istället för föreslagen algoritm för kompensering. Detta leder även till att inga ytterligare krav på sensorer och elektronik tillkommer vilket är en fördel för både processen och miljön.
Projektdemonstator med kronhjul där 9 % av komponentens vikt har sparats in, jämfört med konventionell process. Resultaten tyder även på att ytterligare materialbesparingar kan göras viket minskar mängden material som måste transporteras från smide till bearbetning, minskar mängden spånor som måste skäras bort samt minskar bearbetningstiden.
Projektet visar även att slutresultatet på kronhjul med smidda tandluckor är likvärdigt med konventionell metod i form av hårdhet och distorsion.
En nackdel med bearbetning av ämnen smidda med tandluckor är den ökade ljudnivån i ett bearbetningssteg. Fördelarna med minskad materialtransport, mindre mängd material som måste bearbetas bort och samma slutresultat kan dock ses som större än nackdelen.

2 Executive summary in English

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”Executive summary in English” ska vara skriven på engelska och vara en komprimerad version av rapporten, inte enbart en översättning av den svenska sammanfattningen.

3 Bakground

This project goal was to develop a method for design of the process chain for bevel gear manufacturing with pre-forged blanks. Furthermore, the use of pre-forged blanks in bevel gear cutting allows substantial material saving and reduces the overall process time, due to the lower amount of material that needs to be machined during bevel gear cutting. However, the use of pre-forged bevel gear blanks also introduces new challenges in the process chain. Some of these challenges are interrupted cut in turning of the face cone and machining of forging-scale during bevel gear cutting. Simulation based methods exist for the process design of bevel gear cutting, but they do not consider the mentioned challenges. Furthermore, a precise positioning of the tool in the pre-forged tooth gap in the face milling process is necessary for which no strategies existed before the projct. The hardening distortions was also considered as they may also be affected by using pre-forged blanks due to the banded structure and the segregations in the forging. The impact on the following grinding process was not known and therefore investigated during the project.
In the following sections bevel gear, bevel gear production, state-of-the-art its challenges including simulations will be presented more in detail.

3.1 Bevel gears

Bevel Gears transmit torque and rotation between intersecting or skew axes. They are used for example in automotive or truck applications in the rear axle, in turbines of planes to drive auxiliary equipment, in helicopter transmissions, marine transmissions or industrial gearboxes [KLIN08]. A bevel gear set consists of a pinion and a ring gear. In general the pinion has a lower number of teeth and is used on the driving side on the gearbox and the ring gear has a higher number of teeth and is used at the driven side of the gearbox. By this a fast rotation with a lower torque can be converted into a slow rotation with a higher torque.

3.2 Bevel gear production today

Conventional process chains for ring gear manufacturing start with forged rotational symmetric blanks. In a first stage the outer geometry of the blanks is machined, as depicted in the top of Figure 1, which is followed by a soft machining process for the gear teeth. Typical processes for soft machining are face hobbing and face milling. A significant difference between these processes is the indexing procedure. Whereas face hobbing is continuous indexing process, face milling is a single indexing approach. Subsequently the gear is hardened in a heat treatment process. Here, thermal and thermo-chemical processes are applied. For hard machining of the gear teeth three possible process alternatives exist: lapping, grinding and hard skiving. The choice of the soft machining operations determines the possible hard machining operations. Grinding of bevel gears is only possible, if a face milling process was used for soft machining due to the geometry of the grinding tool. Lapping is possible for both, face hobbed and face milled bevel gears.

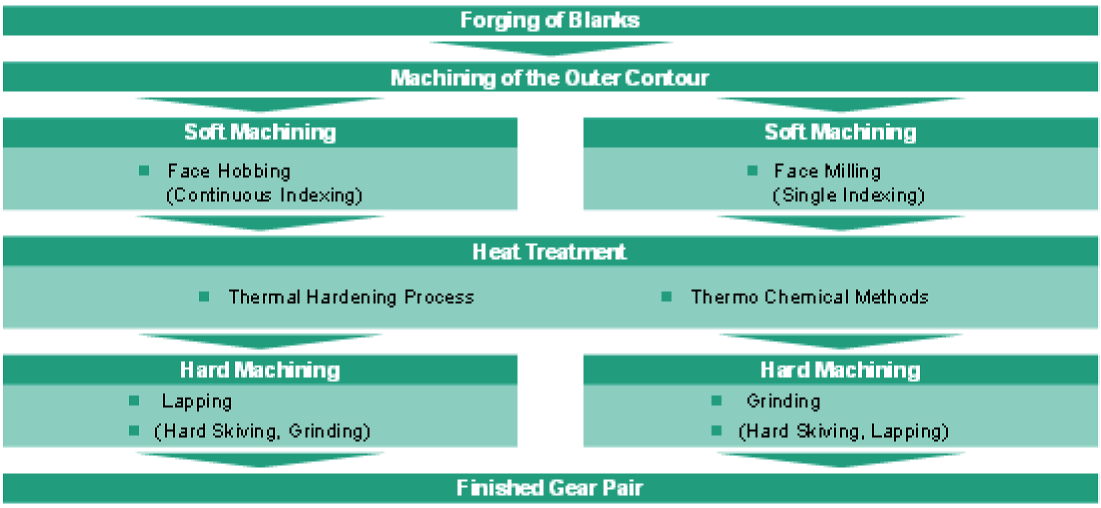

Figure 1, Manufacturing Chains for Bevel Gears [KLOC14].

The manufacturing chain face hobbing followed by lapping is often referred to as being more economical than face milling followed by grinding [STAD08]. However, recent developments have increased the productivity of the face milling followed by grinding process chain. The use of grinding wheels with a high cutting performance increases reachable material removal rates and reduces the grinding times [GRAF13]. Developments in the modeling of the face milling process allow the prediction of tool wear and an optimized cutting process in order to reduce manufacturing costs [HARD13]. Further developments are the use of the flexible kinematics of the bevel gear cutting machine to optimize the potential for the gear design and the use of additional motions to reduce noise excitation caused by oriented structures [STAD08, STAD12]. An advantage of the manufacturing chain using grinding is the option to evaluate the gear quality on a gear measuring machine and to deduct corrections for the manufacturing process. The quality of a lapped gear set is usually tested in a single flank testing and cannot be directly traced back to the lapping process. A methodology for a quality control of the lapping process is part of recent developments [STAD12].

3.3 Future bevel gear production using pre-forged blanks

An alternative process chain is to use precision forging of bevel gears. This is the conventional production method for straight bevel gears used in the differential of rear axles to even the rotation of the output shafts. In this case no machining of the tooth gaps would be necessary which saves the costs for machining and has a high material efficiency since no machining of the gears is necessary. However, for power transmission bevel gears with high demands on power density this technology doesn't reach the necessary tolerances [BADA84], especially not if the gears would be hardened after forging.
Another approach is to use pre-forged blanks at the beginning of the process chain with a near net shape geometry of the teeth. In this case only a small material stock needs to be removed. Thus the machining effort would decrease and the material efficiency would increase. In the following paragraphs the results of a pre-study on the potential material savings is presented. As demonstrator a truck gear is used, which is presented in Figure 2. The gear has an outer diameter of da = 480 mm, z = 40 teeth and a normal module of mn = 10.2 mm. The tooth profile is curved and face milling followed by hardening and grinding is used as gear machining processes to achieve the necessary accuracy.

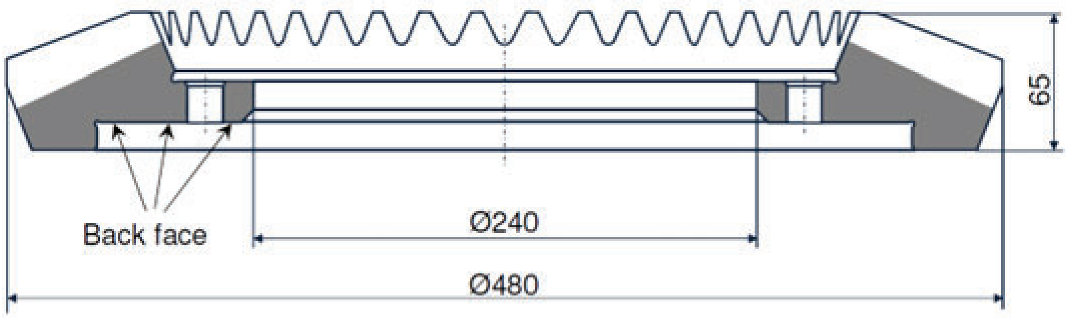

Figure 2, Sample for the Pre-Study [BAGG14].

In Figure 3the result of the pre-study is presented. In the left side of the picture the total mass of the conventional work piece is estimated. This is done by multiplying the area of the cross-section of the workpiece with the circumference in the balance point of the cross-section area. This results in a mass of mWP = 37.8 kg. The middle of Figure 3 shows the result of the calculation of the material mass mGap which needs to be machined. This is made approximately by multiplying the gear width b with the area of the tooth gap Apre in the middle of the gear width and the number of teeth z. For the presented demonstrator the material to be machined during gear milling equals mGap = 8.75 kg which correlates to 23% of the mass of the workpiece mWP. On the right side of the picture is shown, how much material could be saved by using a pre-forged workpiece. A certain stock needs to remain which will be machined by face milling to achieve a good surface quality before heat treatment and grinding of the tooth flanks. The amount of stock is dependent on the geometrical accuracy of the pre-forged workpieces, by the accuracy of the cutting process and the thickness of the forging scale. If a pre-forged workpiece would be used that has a stock of q = 120 μm on the gear flanks, it would be possible to save up to 20% material for the workpiece. But also bigger stocks would allow significant material savings as indicated in the right part of Figure 3. Additional to the material savings the use of pre-forged bevel gears would have the advantage that less material would need to be machined during bevel gear milling and thus it would be possible to reduce the machining time. For the presented sample gear the material to be machined in face milling of the gear teeth would be reduced by up to 87%.

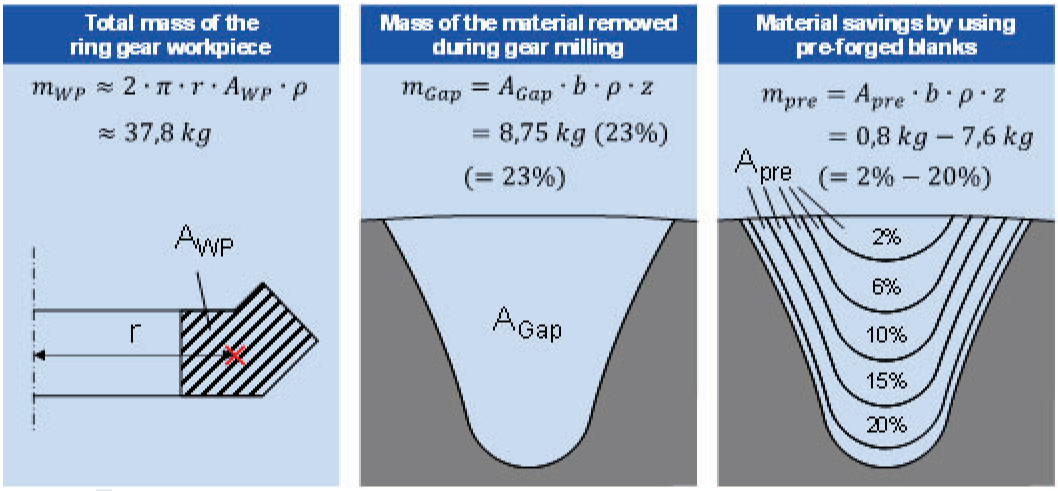

Figure 3, Material saving potential for using pre-forged bevel gear blanks.

3.4 Challenges in machining of pre-forged bevel gear blanks

Figure 4 shows the process chains for conventional bevel gear production with face milling and gear grinding compared to the process chain which uses pre-forged bevel gears. In both cases the same manufacturing steps would be needed, however, with larger modifications. If material should be saved, this of course comes with challenges.

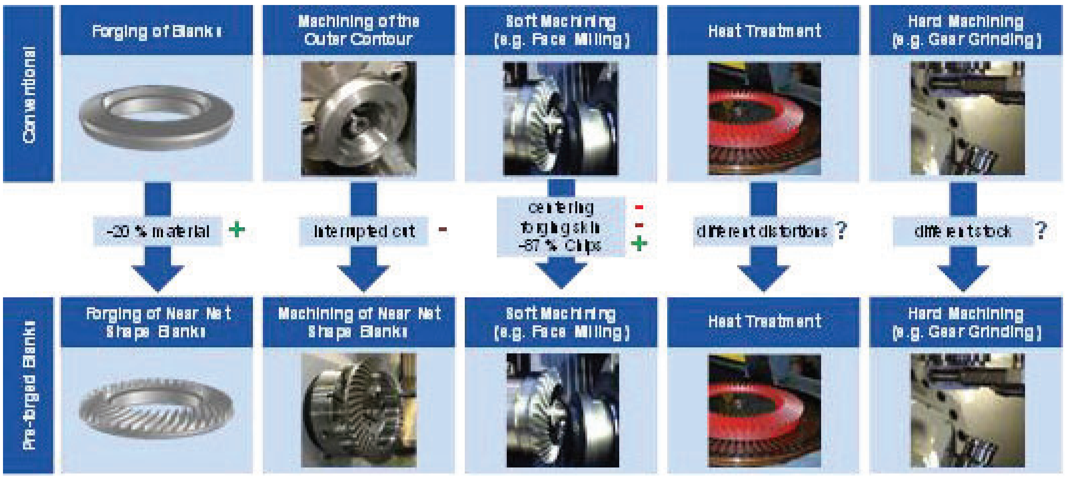

Figure 4, Changes in the process chain for bevel gear manufacturing with pre-forged blanks.

First the blanks would be forged. Afterwards the outer contour is machined, followed by face milling of the teeth, heat treatment and hard machining of the gear flanks and other functional surfaces. Even though the process steps would remain, the use of pre-forged blanks would have a significant impact on the particular process steps. In forging special tools for each gear geometry would be needed to produce the blanks. Furthermore less material would be needed for each blank. The machining of the outer contour of the pre-forged blanks would be influenced by the already existing tooth gaps, especially during the machining of the face cone. The conventional machining of the face cone is continuous turning whereas the machining of the face cone of pre-forged blanks would be turning with an interrupted cut, which is a more challenging process [DEGO11, DEOL09, DINI08]. The major problem of turning with an interrupted cut consists of the dominance of bulk impact loading on the cutting edge generating progressive delamination wear [KLOC05].

Also the soft machining of the gears is affected by the use of pre-forged blanks. In the conventional process chain the workpiece would be clamped in the machine tool without consideration of the rotational position. The rotational position of the first tooth gap can be chosen without any reference. All other tooth gaps will be machined relative to the position of the first tooth gap. If a pre-forged workpiece is used, cutting of the first tooth gap requires a precise positioning of the tool in order to make sure that both flanks of the first pre-forged gap are machined with a similar stock removal. For this a centring strategy is necessary to position the tool accurately in reference to the first tooth gap. Furthermore the face milling process of the gear teeth is affected by the machinability of the forging scale of the pre-forged tooth gap. In conventional face milling the core material of the original blank which has approximately homogenous and isotropic material characteristics is machined. In face milling of pre-forged blanks the flanks of the pre-forged tooth gaps have a forging-scale layer which considerably increases the rate of wear on the cutting tool [TREN59]. At the state of the art no experience about machining a forging-scale layer by face milling exists.

Also the heat treatment will be affected by using pre-forged blanks. The banded structure and the segregations in the forging affect the distortion potential. The pre-forging of the gear teeth will change the appearance of this structure; the bands will follow the gear shape. This will have an effect on the distortions during case hardening and thus also have an impact on the grinding process. This is because the necessary grinding stock could be reduced, if the geometrical deviations after heat treatment are smaller and thus a complete grinding of the tooth flank could be guaranteed even with a smaller grinding stock. This also reduces the required process time in heat treatment, since the required hardening depth prior to grinding is reduced.

3.5 Simulation based process analysis in bevel gear manufacturing

The study of wear and its prediction based on the cutting parameters for geometrical simple processes like turning and milling is in the focus of research since many years [DAMM82, WARD97, KAMM77, OJHA05, TAYL07, ZABE03]. Due to the complex geometric conditions in gear manufacturing this was first possible with the development of numerical calculation methods. For the case of cylindrical gears the process simulation by means of a penetration calculation has been developed in the last 25 years [BOUZ08, HIPK11, MUND92, SCHA12] and has found its way into industrial use. An overview of simulations can be seen in Figure 5

● Simulation Based
◐ Analytical
○ Not Investigated

	Turning	Milling	Gear Milling	
			Cylindrical Gears	Bevel Gears
[TAYL07]	◐	○	○	○
[KAMM77]	○	◐	○	○
[DAMM82]	○	◐	○	○
[MUND92]	○	○	●	○
[WARD97]	◐	○	○	○
[ZABE03]	○	◐	○	○
[OJHA05]	◐	○	○	○
[BOUZ08]	○	○	●	○
[HIPK11]	○	○	●	○
[SCHA12]	○	○	●	○
[HARD13]	○	○	○	●
[HERZ14]	○	○	○	●

Figure 5, Existing methods for the analysis and prediction of tool life.

For bevel gear cutting milling developments started in the recent years. Rütjes developed a simulation based penetration calculation to predict geometrical cutting parameters like chip thickness, cutting speeds, cutting angles, etc. [RUET10] based on the gear data, tool data and process parameters. Hardjosuwito has developed a method to predict tool wear in bevel gear cutting by combining the results from the penetration calculation of Rütjes with results from analogy trials on a lathe which allows a very precise prediction of tool life for conventional bevel gear cutting [HARD13]. Despite the accuracy of the method, it is not yet established in industry, mainly due to the use of inefficient algorithms for the penetration calculation which use a 3D approach. Recent developments in which a 2D approach is used for the penetration calculation of bevel gears allow a time efficient simulation and make the process design of bevel gear cutting by simulative penetration calculation possible for industrial use [BREC15]. Even though this method now allows a fast and precise prediction of tool life it doesn't allow the consideration of inhomogeneous materials as it would be necessary for tool life prediction in the machining of forging-scale.

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4 Purpose, research questions and method

This project has the goal to develop a method to design the process chain for bevel gear manufacturing with pre-forged blanks, see Figure 6 for overall goal

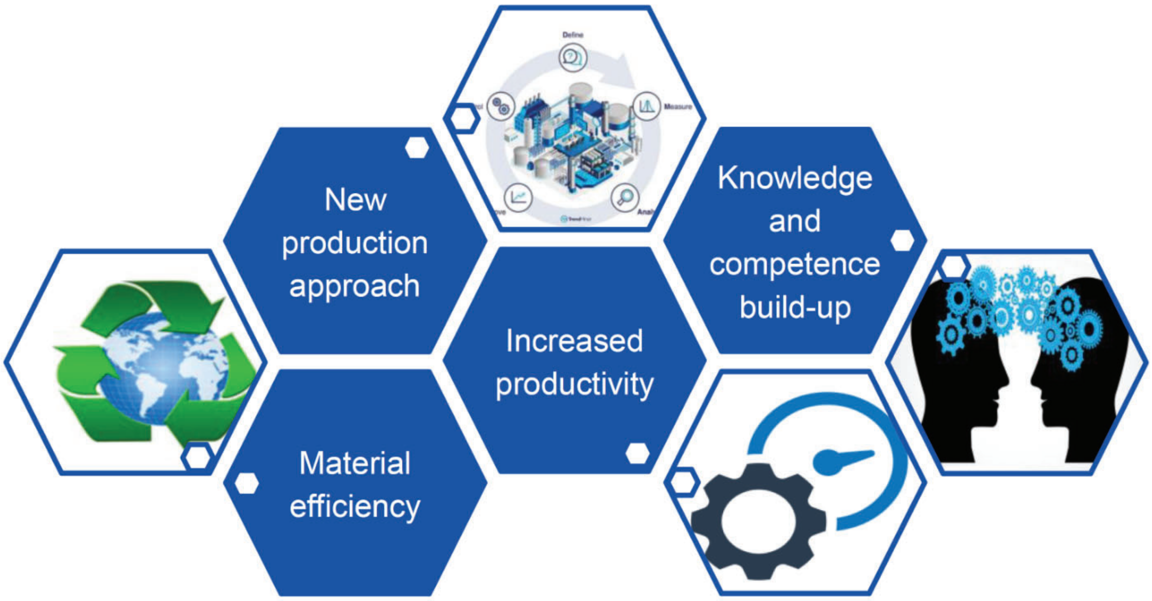

Figure 6, Overall goal of EcoGear.

. The project will be divided into three project parts. One project part is dealing with the development of the pre-forged workpieces (WP1), one part is focussing on soft machining (WP2 to WP6) and one project part is focussing on hardening and hard machining (WP7 and WP8) as presented in Figure 7.

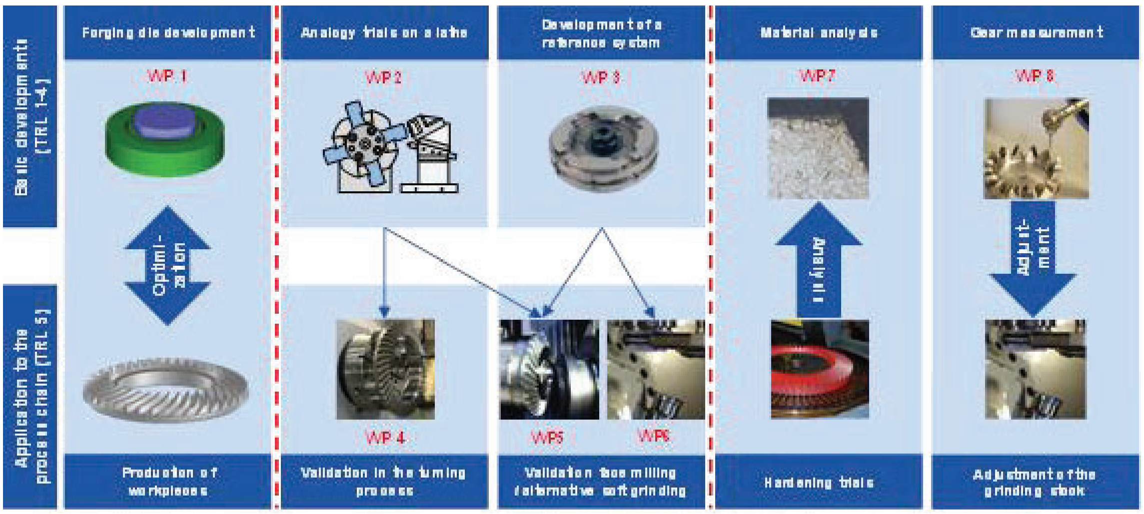

Figure 7, Project Structure

4.1 Research questions

Can manufacturing of bevel gears be more sustainable by using pre-forged blanks?

If so:

What is the new process methodology using pre-forged blanks?
What are the benefits and possible drawbacks with the proposed method?

4.2 Method

The project will derive knowledge by experimental investigations in laboratory and industrial environment. Analogy trials will be utilized for generalization and testing of different process parameters before industrial verification tests are performed.
The project will also use existing knowledge and simulation tool in order to build upon the state of art in bevel gear manufacturing.

5 Objectives

The result of the project will be a more material and time effective production chain for bevel gears, this by using pre-forged blanks. The project aim has several synergies with the vision of the FFI programme.

Environment: The objective of the project is, in correspondence to the FFI sub-program “Miljö”, to reduce the amount of material needed for bevel gear production by using pre-forged near net shape blanks. By that not only the material waste in bevel gear production will be reduced but also the energy and resources needed to produce, machine, transport and recycle the material. Tool life may be increased in face milling because less material will be machined and, if it is proved that hardening distortions are lower than for the conventional process chain, tool life may be increased in grinding due to less stock needed. In a pre-study the potential material savings are estimated to be up to 20% of total weight of the workpiece. In case the workpiece weights 37.8 kg and 80.000 bevel gears are produced per year, this would lead to material savings of ca. 600 t steel per year. For an energy consumption of 19.66 GJ per ton crude steel [SAMA12] this equals to energy savings of 3.3 Mio. kWh per year for the steel production. The amount of chips generated in face milling in a year would be reduced from ca. 700 t to ca. 100 t.

Competitiveness and lead time: In a similar way, the project is also in line with “Konkurrenskraft” and “Ledtid”. To be able to be competitive on a global market in the future, Swedish automotive industry, especially the truck industry, need to withhold a cost-effective production of components. By using pre-forged blanks, delivered from the subcontractor, the total process time will shorten dramatically. In a similar way, pre-forging opens new design possibilities since the cost of machining not needs to be considered.

Collaboration: Furthermore this project will increase the Swedish capacity for research and innovation by increasing the competence in gear manufacturing in the Department for Production Engineering IIP, the PMH Application Lab as well as Swerim, and by improving the collaboration with leading experts in gear technology research as e.g. with the Laboratory for Machine Tool and Production Engineering WZL of RWTH Aachen University and its adjunct R&D platform WZL Gear Research Circle. The cooperation between industry, institute and university will be promoted by involving a full value chain of actors. By involving System 3R, Oerlikon Balzers and Buderus in the project, current and potential subcontractors of Scania are promoted by the project and a cross industrial cooperation is supported. Also the PMH Application Lab will involve student assistants in the work. The student assistants are part time employed at the PMH Application Lab, which gives them the possibility to gain practical experience in R&D supplementary to their studies. For a similar purpose, the project results will be shared both as industrial seminars, but also in relevant courses at KTH.

6 Resultat och måluppfyllelse

Projektets mål har uppfyllts enligt följande:

- Högre effektivitet på materialnyttjande där komponenter med 9 % lägre material har bevisats medan potentialen för 20 % besparing ses som möjlig utifrån de resultat som erhållits i tester
- Högre produktivitet inom produktionen i och med att mindre mängd material måste skäras bort är bevisad
- Framtagen testrig för bearbetningsförsök och data för metamodell
- Ett referenssystem med mekanisk säkerställande av noggrannhet och repeterbarhet är framtaget som ej kräver algoritm för kompensering vid bearbetning
- Simulering av bearbetning av kronhjul
- Rekommendationer för slipning är desamma som för konventionell process
- Dokumentation till projektpartners om riktlinjer och rekommendationer
- Demonstration av bearbetning i industriell miljö tillsammans med projektpartners
- Workshop och digitala möten för informationsspridning av resultat
- Projektresultat kommunicerade i föreläsningar på Kungliga Tekniska högskolan inom kurs för avancerad tillverkningsteknik genomfört de två senaste åren

De omfattande testerna på Kungliga Tekniska högskolan och Swerim har genom experimentell framtagning bidragit till ny kunskap i bearbetning av försmidda ämnen för tillverkning av koniska kugghjul. Dessa har sedan tillämpats i industriell miljö på Scania där även slipning och härdning har studerats.
Simulering av bearbetning av kroniska kugghjul gav resultat för konventionell process medan den för försmidda ämnen ej gav tillförlitliga resultat då beräkningsalgoritmen ej fan en stabil lösning. Förväntad verktygsslitage kunde därmed inte tas fram via beräkningar men experimentell data tyder på att verktygslivslängden motsvarar konventionell bearbetning även om skäret slits på andra ställen längs skäreggen.
Vid verifieringstester i industriell miljö uppstod höga ljudnivåer vid intermittent svarvning vilket vidare bör utredas för eventuell ändring av skärverktyg, processparametrar och påverkan på verktygsmaskinen. Ljudet är främst störande för operatörer som arbetar vid maskinerna och kan medföra att hörselskydd måste användas om inga andra metoder tillämpas för att minska detta.

Den minskade mängd material som måste fraktas från smedjan till bearbetning för att sedan skäras bort ses som en potentiellt stor vinst för miljön. Vidare bidrar det också till att ämne inte behöver lika mycket energi och tid vid bearbetning. Formen vid smide behövs göras men i övrigt kan befintlig produktionsutrustning användas med den nya metoden som föreslås i projektet.

7 Spridning och publicering

7.1 Kunskaps- och resultatspridning

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	x	Bearbetning av försmidda ämnen för tillverkning av kroniska kugghjul var tidigare ej beprövad eller känd
Föras vidare till andra avancerade tekniska utvecklingsprojekt	x	Projektresultaten kan användas för att tas vidare till likande komponenter/produkter där smide till nära slutform är möjlig
Föras vidare till produktutvecklingsprojekt		
Introduceras på marknaden		
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

7.2 Publikationer

Henser, J; Thoors, H; Brohede, U; Design of an analogy trial to capture the influence of surface zone characteristics on tool wear in pre-forged bevel gear machining; 4th International Conference on Gear Production 2021, Germany

Henser, J.; Thoors, H.; Brohede, U.: Design of an analogy trial to capture the influence of the surface zone characteristics on tool wear in pre-forged bevel gear machining In: Forschung im Ingenieurwesen, pp. 4-13, 26 March 2021

Henser, J.: Environmental Friendly Bevel Gear Production by Using Pre- Forged Blanks. In: The Swedish Manufacturing R&D Clusters' Annual Conference, Katrineholm, 2020

Gerrit Stühmeier, Experimental Tool Wear Evaluation for Environmentally Friendly Bevel Gear Manufacturing, M.Sc. Thesis, KTH Royal Institute of Technology, 2021

8 Slutsatser och fortsatt forskning

Tillverkning av koniska kronhjul med försmidda ämnen är möjlig och kan ge en besparing av material på upp till 20 %. Detta medför vinster både för miljö genom minskad transport och leder till konkurrenskraftig produktion genom att den kräver mindre skärande bearbetning.

De farhågor som fanns vid projektstart gällande bearbetning av smidda detaljer med deformationshärdad yta visade sig i praktiken inte vara bekymmersam.

En nackdel med föreslagen metod är den höga ljudnivå som uppstår vid intermittent svarvning. Ett förslag på fortsatt forskning är därför kopplat till detta för att minska ljudnivå och vibrationspåverkan på verktyg och maskiner.

9 Deltagande parter och kontaktpersoner

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