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Small Spur Gear Manufacturing Study

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The objective of this Bachelor's thesis is to examine different manufacturing methods, heat treatment and material options for small spur gears. The thesis was commissioned by Metropolia Motorsport Formula Team and is intended to be used as a guide for further developing the team's 4-wheel drive racecars drivetrain system.

Before the research process a baseline was established by going through the initial plans for the stepped planetary gear intended to be used in the season 2020 racecar.

The process of this thesis was started by familiarizing with both classic gear manufacturing literature as well as more contemporary manufacturing methods. Based on this research significant values for the strength of spur gears were catalogued and presented per each heat treatment method. Manufacturing methods were researched and recorded with notes on their qualities.

These findings were further narrowed down to form the results. Materials for manufacturing were considered during the research but they were not a deciding factor, as most materials are readily available for Metropolia Motorsport through their partners and sponsors.

As a result, a table and more detailed information about three different manufacturing methods were compiled according to the findings from the research in this thesis. In addition, several finishing methods in gear manufacturing were considered and recorded in a table. The complexity of gear manufacturing was clarified and a few suggestions for further development are given in the conclusions.

Keywords	Formula Student, gear drives, drivetrain, spur gears

Contents

List of Abbreviations

HRC	Hardness Rockwell
HV	Hardness Vickers.
HBW	Hardness Brinell.
EDM	Electrical Discharge Machining
WEDM	Wire Electrical Discharge Machining
ME	Quality grade for ISO 6336 standard. ME represents requirements for high degree of operation reliability is required
MQ	Quality grade for ISO 6336 standard. MQ represents requirements achieved by experienced manufacturers at moderate cost.
ML	Quality grade for ISO 6336 standard. ML represents modest demands for material quality and material heat treatment process during manufacturing.
HAZ	Heat Affected Zone. In EDM the heat introduce to the workpiece creates a layer on the cut surface of the material with properties different from the base material.
PBF	Powder Bed Fusion. Additive manufacturing method where metal powder is fused with a heat source.

1 Introduction

Formula student is an international engineering contest for University level students. It is comprised of three different parts: design, manufacturing, and competitions. The goal is to design and manufacture a formula style race car each year, and all participants must be students. Metropolia Motorsport Team was founded in 2000 and has been designing electrical formula style cars since 2013.

The team's goal is to start testing a 4-wheel drive hub motor system with torque vectoring.
With this configuration the car is estimated to be 15kg lighter than before and have 300 Nm more torque compared to a rear-wheel-drive car. Having 4 independent motors for each wheel makes it possible to increase the handling. The previously designed gears were designed with non-standard modulo and thus were extremely difficult to manufacture. Also, the quality and lifetime of wire cut gears for a high-speed gear are suboptimal.

2 Baseline

2.1 Existing layout

Metropolia Motorsport Team has already designed the planetary gear housing with a predetermined planet carrier and the bearing seats for the planet gears. The existing upright works as the gear envelope and has tight space constraints for the gearing. As is clear from image 1, radially it is impractical to enlarge the envelope, as doing so would make render suspension geometry unusable.

To attain the desired gear ratio, which the vehicle simulation subsystem has determined to be between 11:1 to 16:1, preferring higher gear ratios, a planetary gearset with small module small size spur gears must be designed and manufactured. Image 2 shows the free space for the gears to rotate in is also restricted, hence wider, more durable spur gears cannot be used. Helical gears must be taken into consideration, as they provide greater contact surface than regular spur gear.

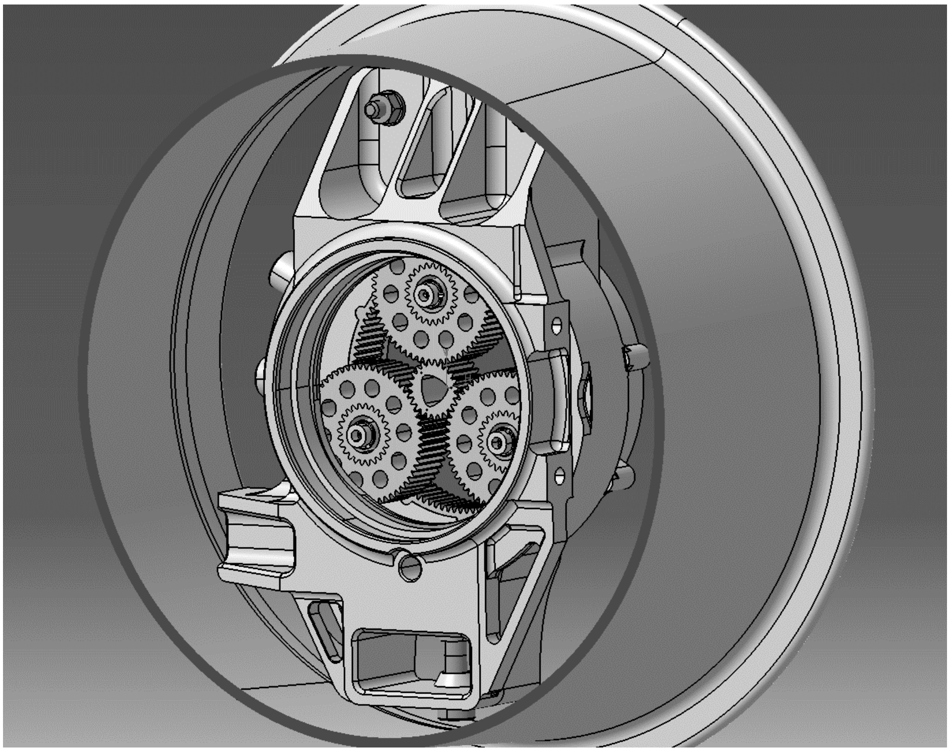

Image 1. Side view of the existing upright which also works as a gear envelope.

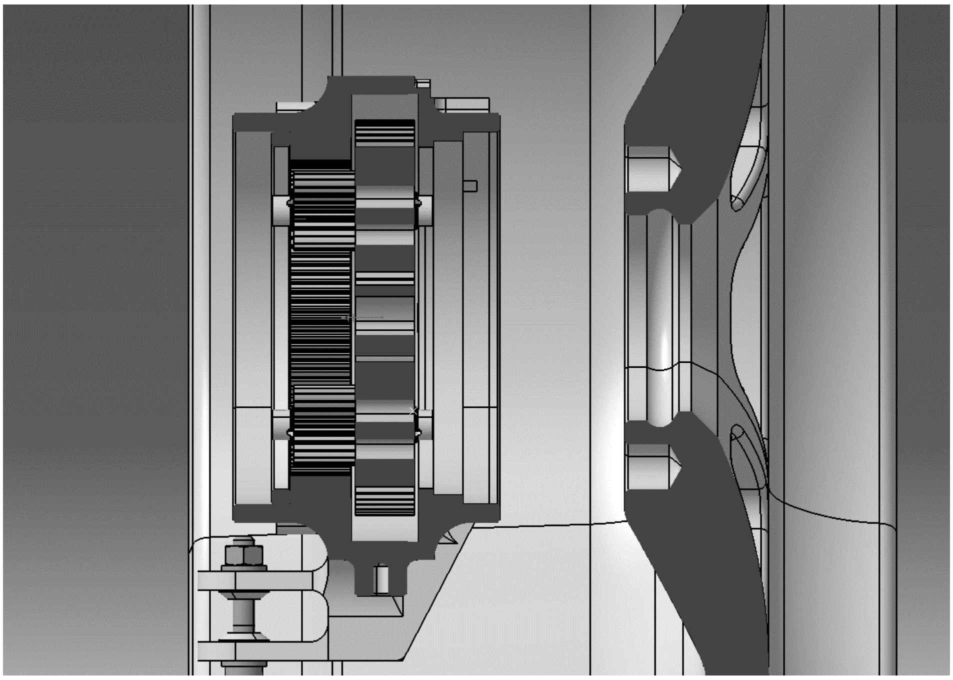

Image 2. Side view of space available for a stepped planetary gear train within the existing layout.

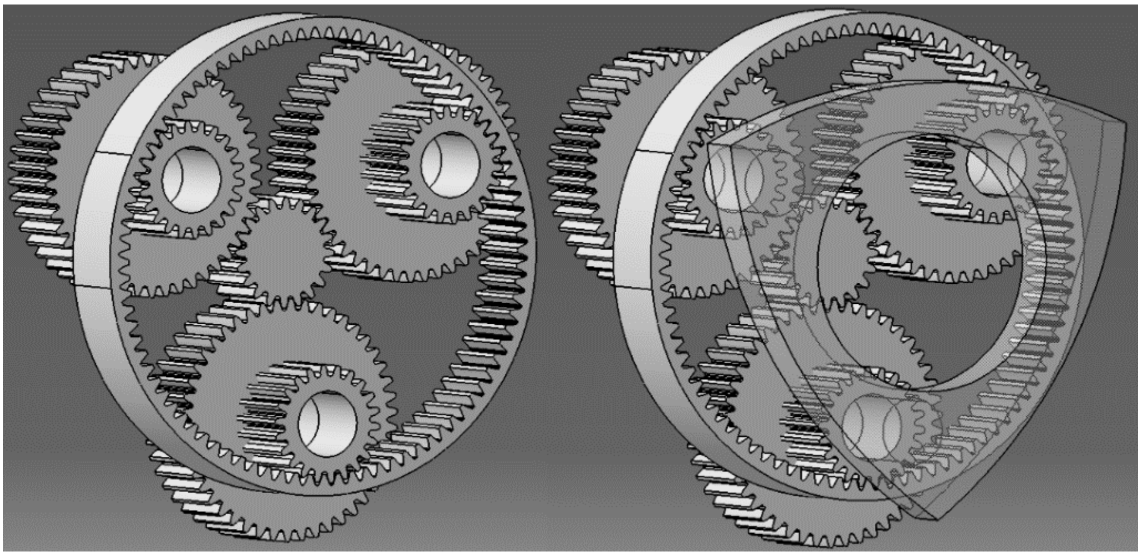

Image 3. Principle picture of the designed planetary gearset.

The motor team has chosen to use the 4-wheel drive formula, which is the Fischer elektromotoren TI085-052-070-04B7S-07S04BE2 with field weakening. This motor is specifically intended for formula student competitions. It is a high-power density electric motor with the following values of interest:

- Nominal torque 11.1 Nm
- Peak torque 29.1 Nm
- Nominal power 15404 W
- Peak power 31199 W
- Maximum speed 20000 rpm
- Weight without housing 2.8 kg
- Total weight of the hub motor assembly:

The first test version of the stepped planetary gear train was manufactured with through hardened XXX steel by wire cutting the involute gearing to the already hardened blanks. Wire cutting is an accurate machining process to cut parts into tight tolerances, but the process creates a heat affected zone of secondary hardening onto the rolling surface of the spur gears.

This will reduce the overall lifetime of the gears, in particular the pitting of the contact surface. According to the running tests previously conducted by the team a better manufacturing method must be found to compete and race with a 4-wheel drive car.

2.2 Planetary gears

The planetary gear train transfers power through two or more load paths, whereas a simple gear mesh has only one load path. They are widely used in automotive and aerospace applications because they provide a significant weight and envelope size reduction. In practice the planetary gearset transfers only torque and all the radial forces are cancelled out. Planetary gear trains are also generally more efficient compared to single mesh gears, since they have stiffer components and relatively smaller parts. Since the input and output shafts are concentric, installation space savings can be significant depending on the application [1].

When designing an in-hub motor 4-wheel drive to a racecar a more compact envelope and lesser weight are a major design comparison benefit. Further space savings for the FS racecar came from the concentric installation of motors inside the wheels of the car, providing more space for the suspension and brake systems.

SFS 3093 standard introduces two sets of recommended modules for gears. The smallest recommended modules are presented in the table below [2].

Table 1. Recommended modules according to SFS 3093.

Set	Modules according to SFS 3093			
1	0.5	0.6	0.8	1
2	0.55	0.7	0.9	1.125

Using these recommended modules to ensure the availability of machining tools the following table with the tooth dimensions are calculated for each of the modules. Calculating the toot dimensions is done according to the formulae in SFS 3094. The height includes the root clearance and hence is 2.25*m. The width is determined at pitch diameter and is 0.5*pi*m [3].

Table 2. Gear tooth dimensions according to SFS 3094 standard.

Gear dimensions								
Dimension	module							
	0.50	**0.55**	**0.60**	**0.70**	**0.80**	**0.90**	**1.00**	**1.125**
Height [mm]	1.1250	1.2375	1.3500	1.5750	1.8000	2.0250	2.2500	2.5313
Width [mm]	0.7854	0.8639	0.9425	1.0996	1.2566	1.4137	1.5708	1.7671

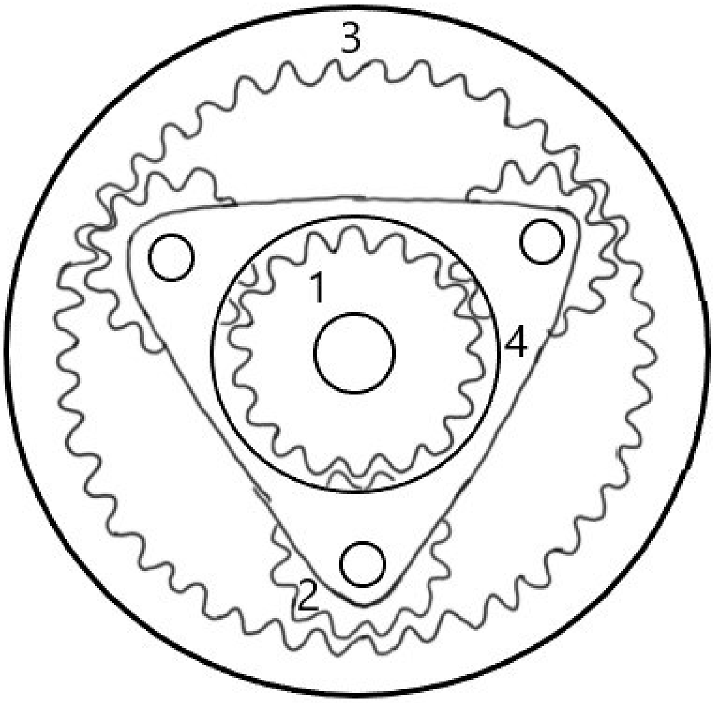

Image 4. The simplest type of planetary gear is called an epicyclic gear and it has the following components numbered in the above picture: a sun gear(1), planet gears(2), a ring gear(3), and a planet carrier(4). When operating the planet carrier rotates about the center of the system, and the planet gears rotate around their own axis and around the center of the system [1].

2.3 Strength calculations

In the design of gears the most relevant aspect to consider is the strength of the teeth transporting power. Generally, these are considered from two distinct perspectives

- Surface pressure on the contact line
- Root bending stress

This thesis uses values for these stresses that have been priorly obtained for Metropolia Motorsport team using SFS-EN 4790 standard. This standard is intended for the strength calculations of industrial gears. More recent and more accurate standards are available. But these standards are beyond the scope of this thesis, since they require the use of pre-existing data and a multitude of different factors, to achieve the highest precision calculations. As the SFS-EN 4790 standard is already based on 1% failure probability. According to the standard a 10% failure probability is allowed for automotive gears [4].

Table 3. Stress values for surface pressure on the contact line and root bending stresses, respectively. Results attained using a calculator build in accordance with the SFS-EN 4790 standard.

Stresses according to SFS-EN 4790		
Contact stress	1200	N/mm^2
Bending stress	900	N/mm^2

The allowable stresses gathered from the ISO 6336 standards are tested for teeth with module from 3 mm to 5 mm. These values were used since they are the most extensive reliable dataset for gear manufacturing. Test runs with manufactured gears are necessary to validate the results of this thesis.

2.4 Goals

The goal of this thesis is to find out possible manufacturing methods for small size high speed planetary gears for Metropolia Motorsport. The first testing of planetary gears is in progress during the writing of this thesis. These gears are wire cut with no finishing operations done on them. The first test is a proof-of-concept type of test. The assemblability of gears is evaluated, and also the functionality and movement of gears are assessed. This testing will provide aid in further developing the Metropolia Motorsports drivetrain.

This thesis aims to provide the team with possible ways of manufacturing small sized high speed spur gears for 4-wheel drivetrains. The goal is to form a table of possible manufacturing methods, with suitable heat treatment options and finishing methods. This thesis will not provide exact material choices but will provide a baseline for available methods from which the team can start the development process in the future, without limiting them to certain predetermined materials or methods. This should improve the starting point of future design, as the team will have pre-existing material available for the design and manufacture of 4-wheel drivetrains.

The results of this thesis are intended as a design aid, but the findings of this thesis should be verified with proper testing of the gears before using them in full capacity.

3 Manufacturing methods

In this chapter several different manufacturing methods are considered for the manufacturing of small sized high speed spur gears. Only manufacturing methods that result in gears with enough durability and load bearing capability will be described in detail.

3.1 Casting

The most used casting method for gear manufacturing is die casting. In die casting the tool-steel mould is filled with a material with a low melting point. When a precision machined mould is used along with a blank design that is not vulnerable to shrinking irregularities the accuracy of the method is similar to a commercial gear cutting [5]. However, as it is evident from the strength tables in the next chapter, cast gears are not sturdy enough for this use case.

3.1.1 Cast iron

The following tables were constructed using reference diagrams from ISO 6336-5 standard for allowable stresses for gears manufactured from different types of cast irons. It is clear from the values from this table that cast iron gears are not suitable for this use, since the allowed stresses are clearly below the set limits for contact and bending stresses [6].

Table 4. Allowed stresses for black malleable cast iron.

Black malleable cast iron							
allowable contact stress [N/mm^2]							
Quality grade	HBW						
	150	175	200	225	250	275	300
ME	N/A	500	530	560	600	-	-
MQ	350	375	425	450	480	-	-
ML	350	375	425	450	480	-	-
allowable bending stress [N/mm^2]							
ME	-	400	430	450	475	-	-
MQ	250	275	300	310	325	-	-
ML	250	275	300	310	325	-	-

Table 5. Allowed stresses for nodular cast iron.

Nodular cast iron						
allowable contact stress [N/mm^2]						
Quality grade	HBW					
	175	200	225	250	275	300
ME	-	550	575	630	660	700
MQ	475	500	525	560	600	630
ML	475	500	525	560	600	630
allowable bending stress [N/mm^2]						
ME	-	440	460	475	485	500
MQ	375	390	400	420	435	450
ML	375	390	400	420	435	450

Table 6. Allowed stresses for grey cast iron

Grey cast iron							
allowable contact stress [N/mm^2]							
Quality grade	HBW						
	150	175	200	225	250	275	300
ME	-	375	420	450	490	525	-
MQ	285	320	340	360	380	-	-
ML	285	320	340	360	380	-	-
allowable bending stress [N/mm^2]							
ME	-	180	190	200	210	220	-
MQ	90	105	120	135	-	-	-
ML	90	105	120	135	-	-	-

3.2 Gear milling

In gear milling a tooth slot at a time is machined and once finished the machining head is moved to the next slot. Gear milling is generally used for manufacturing rack gears and is not capable of the same accuracy as shaping or hobbing [5]. Therefore, it is not further considered in this thesis.

3.3 Gear shaping

Gear shaping allows for both external and internal gears to be machined. In gear shaping a rotating shaper tool is run along the workpiece to form the gears. This process can typically handle face-widths of 0.2 m [5], and hence is suitable for this use case.

The machining values are dependent on the material used for the gears. Modern machines can shape gears to an accuracy where shaving is not required to achieve relatively high precision [5]. Gear shaping can be seen in image 5.

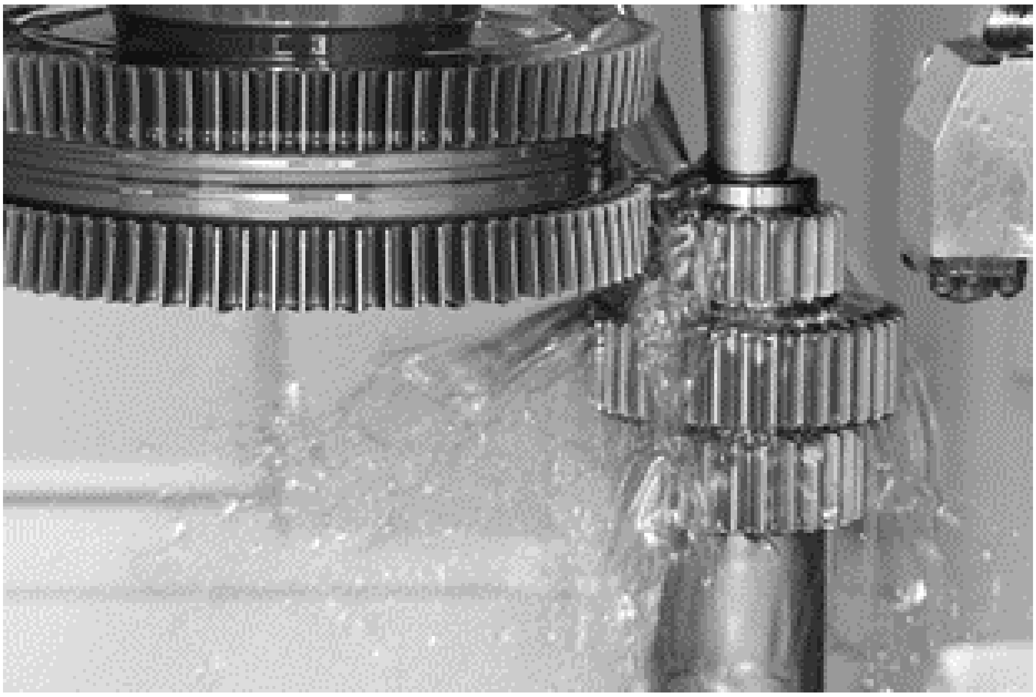

Image 5. Gear shaping with oil as lubricant [7].

3.4 Gear hobbing

Spur gears can be machined by cross feed hobbing. In cross feed hobbing the cutting tool, called the hob, is fed across the face of the gear blank. With this method gears ranging from 2 mm diameter to 10m diameter can be produced. Gears intended for

Metropolia Motorsport suit hobbing well, since the gearing is cut to the whole width of the gear blank, and this allows for clearance for the hob. Hobbing allows for a high degree of accuracy for tooth spacing, and when high accuracy is needed a two-stage cutting with rough cut and finishing cut is commonly used.

The best surface finish is acquired by using single thread hobs. If the gears are shaved or lapped after hobbing the accuracy from hopping is not so important. Only external gears can be produced with hobbing, however skiving, an analogous process to hobbing, is used in manufacturing internal gears. Machining values are dependent on the material used for the gears, and machining values must be considered on a material basis when hobbing gears [5]. A gear hobbing machine can be seen in image 6.

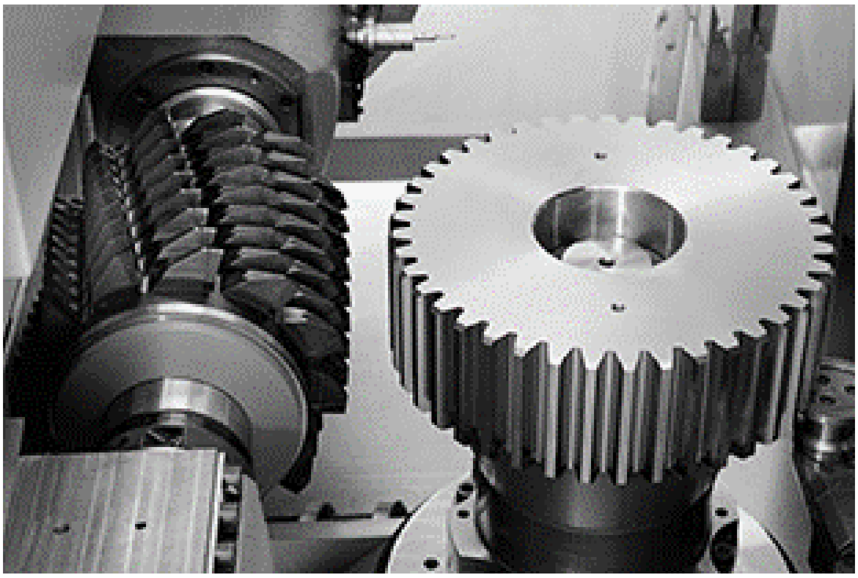

Image 6. Gear hobbing machine with multiple thread hob [8].

3.5 Electrical discharge machining

In EDM an electrical current is passed from the tool (electrode) through a medium to the workpiece. This current travels as a spark and removes small particles from the workpiece. Discharges happen thousands of times per second, and always between the shortest distance between the tool and the workpiece. A clearance between the workpiece and tool must be always maintained. Both the tool and workpiece must be electrically conductive for the method to work. The tool removes a part of the workpiece that is a projection of its own shape from the workpiece. This projection is always larger than the tools actual size because of the clearance.

In WEDM the electrode is a thin copper of tungsten wire is used to cut grooves into the workpiece. To keep the wire from overheating it is moved from the feeding coil to a collection coil. The numerical control of the machine allows for complicated shapes to be cut from the workpiece. Hence it is suitable for machining spur gears if the grooves of the gears are wider than the diameter of the wire plus the clearance.

EDM being a thermal process, where the workpiece is heated during machining dimensional distortions may occur and the normalization of the workpiece may be needed. The introduction of heat to the workpiece also creates a HAZ (Heat affected Zone) on the surface of the cuts with a typical thickness of 0.05 mm. For high stress conditions in end use it is sometimes necessary to completely remove the HAZ layer [9]. A wire cutting machine with cut gear can be seen in image 7.

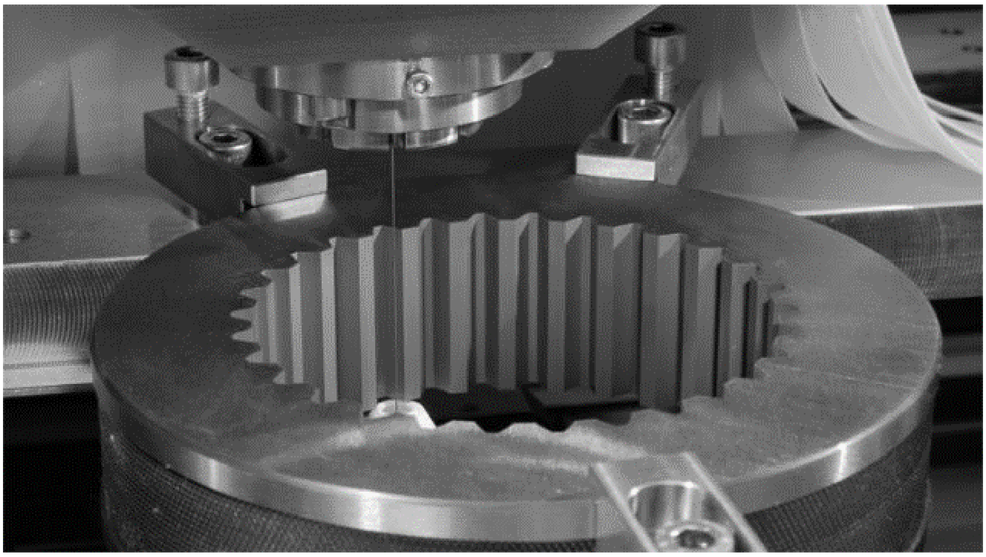

Image 7. Wire cutting machine with cut gear [10].

Without any testing results available now it will be assumed that removing the HAZ layer is needed for the proper function of high-speed planetary spur gears, as the cracks in the HAZ layer may propagate and cause failure.

3.6 Additive manufacturing

In additive manufacturing a three-dimensional computer-generated model is used to manufacture a part by adding material to the workpiece in thin layers. Compared to conventional machining this allows for more complex shapes to be manufactured without restrictions created by machining tools available. Rapid prototyping is a typical use case for additive manufacturing.

For metal additive manufacturing powder bed fusion or PBF is a common method. Laser sintering PBF is a process where the metal powder is fused together without fully melting the metal powder. Parts produced by laser sintering are typically ready for use once manufactured. But for gear manufacturing, the gears must be heat treated before use, to achieve acceptable load bearing capability [10]. Powder bed fusion can be seen in image 8.

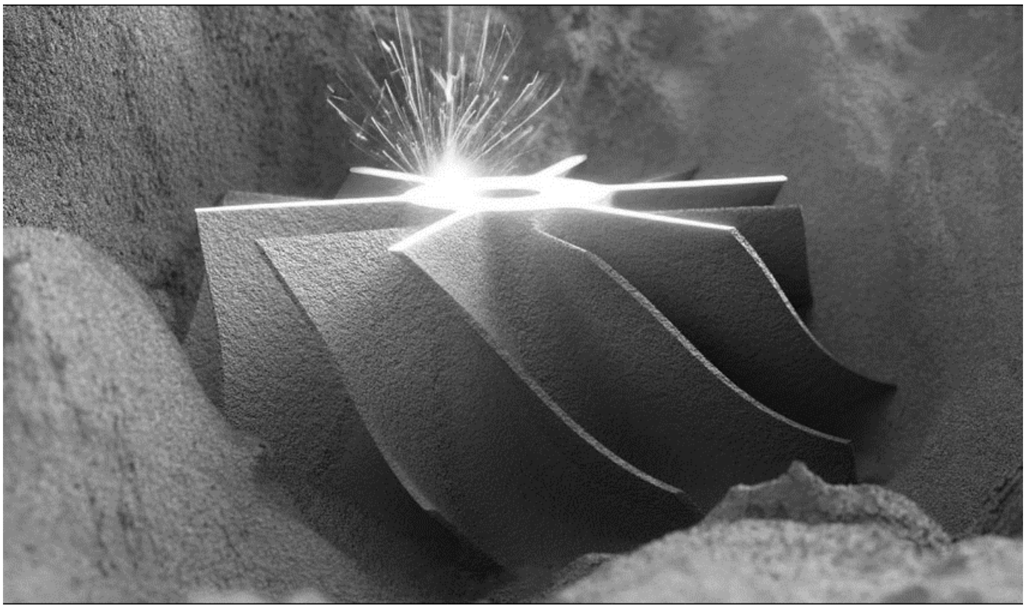

Image 8. PBF with a laser manufacturing a complicated 3D part [12].

3.7 Finishing operations

Several finishing operations are in widespread use in industrial gear manufacturing. High pitch line velocity gears require high precision manufacturing, and finishing methods are used to improve gear quality after machining and to remove distortions from heat treatment [5].

Generally, the better the gear accuracy, the better the quality and durability of the gear. However, the cost of manufacturing is significantly higher for the better accuracy classes of gears. ISO, AGMA and DIN standards for gear accuracy levels are available. Gear accuracy is a complex matter with many different factors. These factors include the method, machine operator's skill, material, heat treatment etc. Typically, when machining gears are first machined to dimensions close to final dimensions, then heat treated and ground to final dimensions, and for the highest surface quality they can be lapped after grinding [5]. The following finishing methods are chosen from the literature as the most general higher accuracy level methods.

3.7.1 Grinding

Grinding is used as it is difficult to cut hardened parts, and small module gears can be ground from a solid. More typically a machined gear is ground to final dimensions and surface finish after heat treatment. Many different grinding tool types are used for grinding gears [5]. For this thesis it is not required to examine these as the results of these grinding methods are similar.

3.7.2 Shaving and Honing

Shaving is a finishing process done by cutting and is generally considered a faster process than grinding. Since the parts are typically not heat treated between machining and shaving, only a small amount of stock is needed for shaving. Heat distortions are handled by other than finishing methods such as keeping them to a minimum and allowing for clearance by shaving [5].

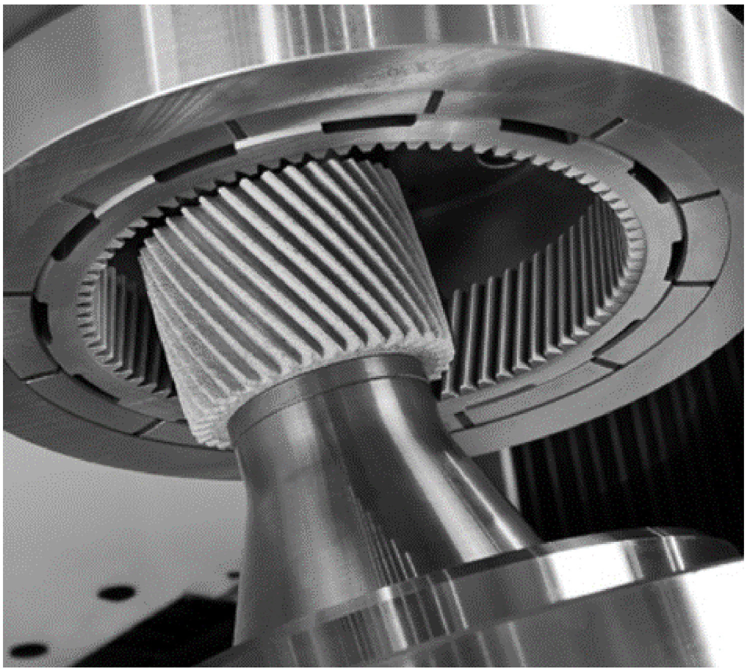

Image 9. Honing an internal gear with a honing tool [13].

Honing uses an abrasive gear shaped tool, seen in image 9, rolled against the workpiece. This process is done with a suitable lubricant. The honing process averages the surface roughness, but the effect on gear accuracy is minimal and mostly down to the machining process. Honing is used in high-speed gear manufacturing after the heat treatment of already accurate gears to remove oxidation and some of the heat treatment distortion. This ensures very smooth surface finish that decreases failure through scoring and to achieve a higher load carrying capacity. Honing typically removes very little material from the workpiece [5].

3.7.3 Lapping

In gear lapping a fluid infused with abrasive particles is used between the workpiece and the lapping tool. The tool and the workpiece move in at least two directions relative to each other. The tool has a similar shape to the gear to be lapped. Lapping can be done manually or with a machine. Particles used in the lapping fluid are typically of silicon carbide, chrome oxide or industrial diamonds. These abrasive particles are typically mixed with cutting oil. It is possible to do lapping between two workpieces. Lapping is a suitable finishing method for all hard materials [14]. In image 10 an industrial lapping of gears can be seen in action. As other finishing operations, lapping improves the wear properties of the gears by smoothening the surface. Lapping gears together without a tool appears to be an interesting possibility for the team to manually mate gears in certain planetary gear together.

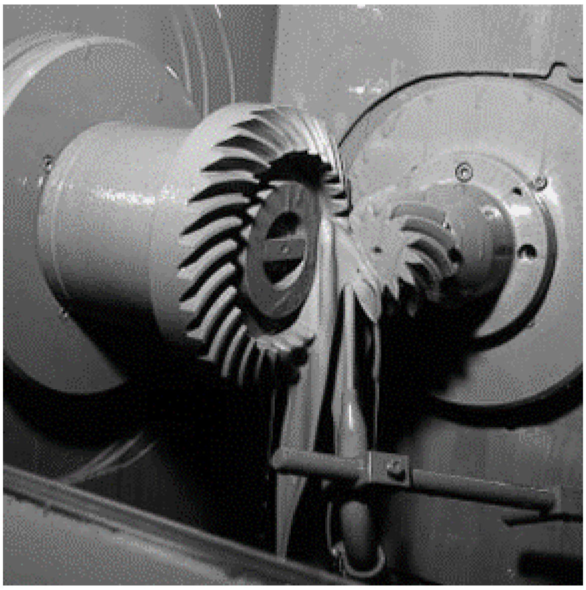

Image 10. Lapping of helical gears using an industrial lapping machine with a lapping fluid [15].

4 Heat treatment options and suitable materials

Hardening is a well-known method to increase the durability and hardness of the workpiece. Hardening is a three-stage process, and in the first stage the workpiece is heated to austenisation region. In the second stage the workpiece is cooled rapidly and finally in the third stage the workpiece is annealed by first raising its temperature and then letting it cool down slowly. All the temperatures used are dependent on the material used.

Hardening leaves a stress into the surface workpiece. With through hardening there is typically tensile stress remaining, which lowers the durability of the workpiece against periodic and fatiguing strain. In materials with a low hardening depth the remaining stress is compressive, and thus increases the surface durability. [16].

Allowable stresses for normalised and cast steels are shown in the tables 7 and 8 below. Information for the tables was collected from the ISO 6336-5 standard. It is clear from the values that nonhardened steels are not suitable for this use, since the allowed stresses are below the calculated values for the contact and bending stress.

Table 7. Allowable stresses for normalized low carbon steels.

Wrought normalised low carbon steels				
allowable contact stress [N/mm^2]				
Quality grade	HBW			
	125	150	175	200
ME	425	475	525	555
MQ	320	340	360	385
ML	320	340	360	385
allowable bending stress [N/mm^2]				
ME	390	410	425	450
MQ	250	275	300	325
ML	250	275	300	325

Table 8. Allowable stresses for cast steels.

Cast steels			
allowable contact stress [N/mm^2]			
Quality grade	HBW		
	150	175	200
ME	415	445	460
MQ	280	310	335
ML	280	310	335
allowable bending stress [N/mm^2]			
ME	350	360	375
MQ	215	225	250
ML	215	225	250

4.1 Through hardening

In the tables from 6 to 9 the allowable contact and bending stresses according to the ISO 6336-5 standard are presented. The values indicate that through hardening is not a suitable hardening method for the gears in this use. Both allowed contact and bending stresses are below the calculated values.

Table 9. Allowed contact and bending stresses for through hardened wrought carbon steels with nominal carbon content of 0.20% or higher.

Through hardened wrought carbon steels			
allowable contact stress [N/mm^2]			
Quality Grade	**HV**		
	150	175	200
ME	560	575	600
MQ	500	525	550
ML	425	450	475
allowable bending stress [N/mm^2]			
ME	490	505	515
MQ	400	415	430
ML	295	310	325

Table 10. Allowed contact and bending stresses for Through hardened wrought alloy steels. ME quality grades were obtained without pitting stabilization.

Through hardened wrought alloy steels							
allowable contact stress [N/mm^2]							
Quality Grade	**HV**						
	200	225	250	275	300	325	350
ME	700	750	820	875	925	980	1040
MQ	640	670	700	725	770	800	830
ML	450	480	525	550	575	615	645
allowable bending stress [N/mm^2]							
ME	610	625	640	660	675	700	720
MQ	540	570	585	610	625	650	675
ML	375	400	420	430	475	480	510

Table 11. Allowed contact and bending stresses for through hardened cast carbon steels with nominal carbon content of 0.20% or higher.

Through hardened cast carbon steels			
allowable contact stress [N/mm^2]			
Quality Grade	**HV**		
	150	175	200
ME	490	525	540
MQ	430	450	470
ML	430	450	470
allowable bending stress [N/mm^2]			
ME	400	425	450
MQ	300	310	325
ML	300	310	325

Table 12. Allowed contact and bending stresses for through hardened cast alloy steels.

Through hardened cast alloy steels							
allowable contact stress [N/mm^2]							
Quality Grade	**HV**						
	200	225	250	275	300	325	350
ME	625	660	690	725	760	785	825
MQ	550	575	610	640	675	720	745
ML	550	575	610	640	675	720	745
allowable bending stress [N/mm^2]							
ME	510	530	550	565	580	600	625
MQ	470	490	500	525	550	560	575
ML	470	490	500	525	550	560	575

4.2 Carburizing

According to Kivivuori and Härkönen carburizing a 0.3-2.5 mm thick layer with carbon content of 0.6-1.0% is achieved by keeping a low percentage carbon steel (0.15-0.25 %C) within the austenisation region in the presence of carbon donating material, typically a gas. This treatment leaves a hard surface on the workpiece, but since the depth of the carburization is no more than 2.5 mm the inside of the workpiece retains the base steels material properties [17].

Surface hardness depends on the carbon content and typically a 0.6-0.8% C yields the hardest surfaces. The target value for surface hardness is typically between 59 and 63 HRC. The other alloys in steel affect the hardness to a small degree. Carburisation is a well-suited method for manufacturing gears, as the hard surface carries higher surface pressures, and the compressive stress increases resistance to fatigue. Good bending resistance can be attained by choosing a suitable base steel alloy that must be hardening but must not become too hard.

The best results regarding fatigue strength are attained when the hardness difference between the surface and inner material is around 30 HRC. The best suited carburisation depth is typically between 0.15 to 0.25 times the modulus of the gear [17]. According to this, the following carburizing dimensions are calculated for the intended size of gears.

Table 13. The calculated recommended carburising depths

Calculated carburising depth [mm]			
Modulus	**Depth factor**		
	0.15	0.20	0.25
0.50	0.08	0.1	0.125
0.60	0.09	0.12	0.15
0.70	0.11	0.14	0.175
0.75	0.11	0.15	0.1875
0.80	0.12	0.16	0.2
0.90	0.14	0.18	0.225
1.00	0.15	0.2	0.25

As it is clear from the table above, all the recommended carburising depths are below the minimum carburising depth of 0.3 mm. Thus, in the results 0.3 mm will be used as a recommended carburising depth.

The surface hardness of carburised workpieces can be increased with shot peening. With this method small steel balls are blown onto the surface of the workpiece at high-speed using air pressure. The balls cause deformation on the surface by stretching it, creating a compressive stress on the surface. This compressive stress increases the durability against micro pitting corrosion [6].

According to SFS-ISO 6336-5 6.7.2 shot peening improves root bending strength of the gear teeth. With quality grade ML, no increase is expected. For MQ the allowable number is increased by 10% and for ME the increase is 5%. Shot peening may cause undesired lowering of pitting resistance due to higher surface roughness, and refinishing methods may be required. Post shot peening processes may also affect the residual compressive stress and thus the bending strength [6].

Table 14. Allowed contact stress for carburized gears.

Case hardened wrought steels allowable contact stress [N/mm^2]	
Quality Grade	HV 600-800
ME	1650
MQ	1500
ML	1300

Table 15. Allowed bending stress for carburized gears.

Case hardened wrought steels allowable bending stress [N/mm^2]	
Quality Grade	HV 600-800
ME	1050
MQ	850-1000
ML	620

As seen in tables 14 and 15 carburising is a viable heat treatment option for the gears in question.

4.3 Nitriding

Many different methods for nitriding exist, but in all of them nitrogen is introduced to the workpieces at such a low temperature that phase transformations cannot occur. Due to the lack of phase transformations, the dimensional changes of the workpiece are minimal. The temperature range of nitriding is between 450 to 600 C. Surface hardness is achieved with nitrides formed on the work piece’s surface and a nitrogen diffusion layer is formed under the nitride layer.

Different nitriding methods:

- Plasma nitriding. Accurate method, suitable for stainless steels. Requires expensive equipment.
- Gas nitriding. Small dimensional changes due to low temperature, long treatment time.
- Nitrocarburizing. Short treatment time due to higher treatment temperature. Larger dimensional changes due to higher temperature.
- Negative pressure nitriding. Accurate control over the treatment atmosphere, allows nitriding for deep holes. Time consuming and expensive treatment.
- Salt bath nitriding. Cheap and fast nitriding method, suitable for nitriding stainless steels. Not in use in Finland, contaminating and environmental problems.

The typical depth of the nitriding layer is 0.2-0.5 mm, and the achieved hardness is between 500 and 1200 HV. Stresses in the workpiece from machining can be triggered at nitriding temperatures, and cause dimensional changes, but this can be prevented by stress free annealing at the appropriate work stage. Almost all steels can be treated by nitriding, however special nitriding steels exist.

Nitrocarburizing is a modification of nitriding. With this modification carbon dioxide is added to the treatment and the goal is to form carbonitrides on the surface of the workpiece. With this method the surface is not as hard as with nitriding, but the treatment time is reduced. Temperature used with this method is approximately 570 C [16]. In tables 16 and 17 the allowable stresses for nitrided and nitrocarburized steels are represented.

Table 16. Allowable stresses in nitriding steels according to ISO 6336-5.

Nitriding steels hardened tempered and gas nitrided allowable contact stress [N/mm^2]		Through hardening steels hardened tempered and gas nitrided allowable contact stress [N/mm^2]	
Quality Grade	HV 650-900	Quality Grade	HV 450-650
ME	1450	ME	1215
MQ	1250	MQ	995
ML	1125	ML	790
Nitriding steels hardened tempered and gas nitrided allowable bending stress [N/mm^2]		**Through hardening steels hardened tempered and gas nitrided allowable bending stress [N/mm^2]**	
Quality Grade	**HV** 650-900	**Quality Grade**	**HV** 450-650
ME	940	ME	875
MQ	840	MQ	720
ML	540	ML	510

Table 17. Allowable stresses in nitrocarburized steels according to ISO 6336-5.

Wrought steels nitrocarburised allowable contact stress [N/mm^2]								
Quality Grade	HV							
	300	350	400	450	500	550	600	650
ME	775	835	890	950	950	950	950	950
MQ	775	835	890	950	950	950	950	950
ML	650	650	650	650	650	650	650	650
Wrought steels nitrocarburised allowable bending stress [N/mm^2]								
Quality Grade	HV							
	300	350	400	450	500	550	600	650
ME	580	640	700	760	760	760	760	760
MQ	580	640	700	760	760	760	760	760
ML	450	450	450	450	450	450	450	450

4.4 Carbonitriding

Carbonitriding is a modification of carburising heat treatment. In this method nitrogen is added with carbon while hardening, typically with gas or salt bath. The goal of adding nitrogen is to increase the surface hardness, increase wear resistance and slow down the hardness reduction during annealing. Typically, the hardening temperature is lower than with carburising, around 875 C, and ammonia is added during or towards the end of carburising. Thin carbonitrided surfaces do not necessarily need annealing [16].

4.5 Induction and flame hardening

In induction and flame hardening the workpieces surface is heated to a depth of 0.5-10mm. The two methods differ only with the heating method. Induction hardening uses AC-current to heat the workpiece with heating coil. Flame hardening uses a flame to heat the workpiece. Today induction hardening is more prevalent in the industrial use as a heating method. After heating the workpiece to A3 temperature, it is quenched by spraying water. After quenching the workpiece is annealed.

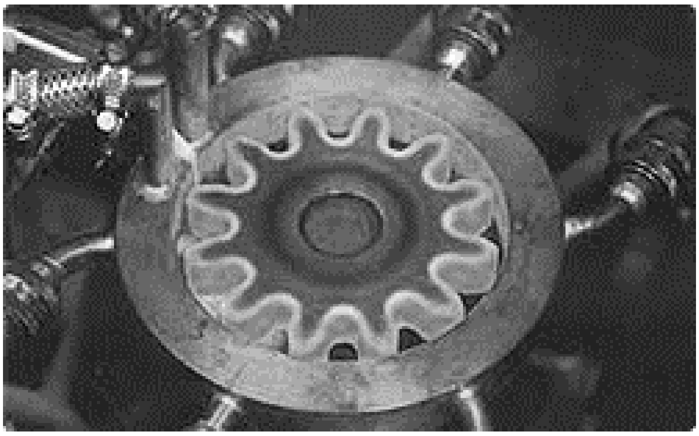

Image 11. Gear induction in process [18].

A martensitic microstructure is achieved to the surface of the workpiece, and a large pressing strain, since the surface area increases when martensite is formed. With martensitic surface, a good surface pressure durability and a greater abrasion resistance is achieved. This method is fast, but the purpose made heating coils make small scale manufacturing expensive. Using this method only a single workpiece can be processed at a time [16]. The process can be seen in image 11.

Table 18. Allowable stresses in flame or induction hardened steels according to ISO 6336-5.

Flame- or induction-hardened wrought and cast steels allowable contact stress [N/mm^2]					
Quality Grade	HV				
	500	525	550	575	600
ME	1270	1280	1290	1310	1320
MQ	1150	1160	1180	1190	1210
ML	975	990	1010	1025	1050
Flame- or induction-hardened wrought and cast steels allowable bending stress [N/mm^2]					
Quality Grade	HV				
	500	525	550	575	600
ME	740	460	780	790	800
MQ	720	725	730	730	730
ML	450	475	490	505	525

5 Results

Before further comparing the different manufacturing methods all the suitable hardening methods are compared to the calculated contact and root bending stresses. All manufacturing, finishing and heat treatment methods have been gathered into the three tables 19-21. The tables are used to compare the different methods. From the data acquired only carburising and nitriding are viable options. And from these methods only the highest quality standard can be seen suitable for the stresses involved in the planetary geartrain in question. Therefore, the manufacturing methods must be screened in detail and the highest available accuracy must be chosen.

Table 19. Comparison between different heat treatment options.

Heat treatment options				
Metric	Through hardening	Carburisign	Nitriding	Induction/flame hardening
Max allowable stresses contact/bending [N/mm^2]	1040/720	1650/1050	1450/940	1320/800

Table 20. Different manufacturing methods listed with meaningful metrics.

Manufacturing methods					
Metric	**Casting**	**Shaping**	**Hobbing**	**EDM**	**AM**
Accuracy (1-5) scale	3	4	4	3	3
Tools	Molds	shaper	Hobs	None	None
Need fot subcontracting	Yes	Yes	Yes	Yes	Yes
Max allowable stresses contact/bending [N/mm^2]	700/500	1650/1050	1650/1050	1650/1050	1650/1050
Other factors	Mold design is a time consuming process	Tools available only with standard modules. Expensive tools	Tools available only with standard modules. Expensive tools	HAZ layer, no limit on shape other than wire clearance	no limits on shape. Needs annealing after printing

Table 21. Comparison between different finishing methods.

Finishing methods				
Metric	**Grinding**	**Shaving**	**Honing**	**Lapping**
Surface finish	The level of surface finish is assumed similar across the			
Tools for the method	Gear grinding tool, mainly available in standard modules	Shaving tool, mainly available in standard modules	Honing tool, mainly available in standard modules	Lapping fluid
Need for subcontracting	Yes	Yes	Yes	No
* in case lapping is done by the team themselves the surface finish might not reach the same level as trained profeccionals can.				

Below three different manufacturing methods are examined based on the findings on the literature research in this thesis. All these manufacturing methods need to be verified by testing before adopting the methods for further use in the formula student styled race car. The methods are presented in the tables 22 and 23, which includes the gear forming methods with key figures for them, suitable heat treatments for each of the manufacturing methods, and possible finishing methods for them.

Table 22. Suitable manufacturing methods and differences between them.

Manufacturing method			
Metric	**Wire Cutting**	**Additive manufacturing by PBF**	**Hobbing or Shaping**
Highest possible accuracy class (1-5 scale)*	3	3	5
Suitable heat treatment methods	Case hardening	Case hardening	Case hardening or Nitriding
Additional heat treatments	Removal of HAZ	Annealing after PBF	None
Tools required for manufacturing machinery	None	None	Hob or shaper tool
Max. Allowable contact stress [N/mm^2]**	ME 1650	ME 1650	ME 1450
	MQ 1500	MQ 1500	MQ 1250
	ML 1300	ML 1300	ML 1125
Max. Allowable bending stress [N/mm^2]	Me 1050	Me 1050	ME 940
	MQ 1000	MQ 1000	MQ 840
	ML 620	ML 620	ML 540
* based on Hobbing and shaping being common industrial methods, and performed by profeccionals who work with gears daily, whereas both wire cutting and PBF are done by profeccionals, but are not in huge industrial wide use as of now.			
**Shot peening can be used to inrease surface durability, but might effect the bending durability.			

From these tables I have compiled three suggestions for manufacturing the gears for a Formula Student racecar. Lapping the paired gears with a suitable lapping fluid, appears to be a good choice for a finishing method. This is because the lapping can be done by the team thus reducing the cost of the gears and it ensures the proper function of the gears relative to one another in the planetary gear. Lapping the gears in pairs also removes the need for a special finishing tool, further driving the cost of the process down.

Table 23. Table showing differences of finishing methods.

Finishing methods				
Metric	**Grinding**	**Shaving**	**Honing**	**Lapping**
Surface finish	The level of surface finish is assumed similar across the methods*			
Tools for the method	Gear grinding tool, mainly available in standard modules	Shaving tool, mainly available in standard modules	Honing tool, mainly available in standard modules	Lapping fluid
Need for subcontracting	Yes	Yes	Yes	No
* in case lapping is done by the team themselves the surface finish might not reach the same level as trained profeccionals can.				

5.1 Wire cutting and case hardening

Wire cutting the gears from a suitable case hardening steel alloy appears to be a suitable and readily available manufacturing method. The exact material needs to be chosen based on strength calculations and materials available for the team. After wire cutting the HAZ is removed by suitable heat treatment before case hardening the gears to the desired hardness. This ensures that the optimal qualities of spur gears can be reached, and further finishing methods can be used to further optimize for load bearing durability. This method allows much freedom in the design of the gears, as the module can be freely chosen, if there is enough clearance for the wire to move in the grooves of the gear teeth.

5.2 Additive manufacturing and case hardening

As mentioned before additive manufacturing allows for easy testing of new drivetrain and gear designs. Also, the quality of the gears and their load bearing capability can be improved by annealing and case hardening the parts before use. For example, maraging steel appears to fill the strength requirements for load bearing and is suitable for case hardening. As with wire cutting, module and other gear dimensions can be freely chosen.

5.3 Hobbing or shaping gears and nitriding

According to the ISO standard 6336 nitrided gears achieve the highest load bearing capacity, at least in industrial applications with long lifecycles. Following this hobbing or shaping gears allows the use of nitriding steels that can be surface finished before nitriding. If the loads in the testing of the gearing show the need for higher durability this method should be considered. However, hobbing and shaping both require special tools, that are available only with certain standard modules, see table 1, which limits the design process. This is similar for the finishing operations that use special shaped tools in the process.

6 Conclusions and further development

Several different manufacturing methods are available for small sized spur gears, and thus it would make most sense from Metropolia Motorsports viewpoint to start testing with the cheapest and most readily available methods and accumulate data on small spur gears to further develop the cars drivetrain. Based on these results and more knowledge more complicated manufacturing methods might be chosen.

Should the gear strength calculations change in the future by improved calculation methods or improved calculation accuracy by collecting and comparing data on gear lifetime, the findings can still be used, but the resulting tables must be updated according to the new strength calculation stresses.

In conclusion this thesis has reached the goals set for it and as such should provide Metropolia Motorsport with reasonable information for continuing with the drivetrain design.

6.1 Helical gearing

According to all the source material, a greater load carrying capability can be achieved with helical gears. So far only spur gears have been considered due to the previous research of the team indicating that machining spur gears are readily available and within the scope of the team. However, if testing proves that spur gears fail to meet the criteria, helical gearing would be the recommended next development step.

6.2 Composite gears

While researching different materials and manufacturing methods for planetary gears, it became clear, that to achieve enough root bending resistance while simultaneously maintaining enough toughness to withstand the surface pressure it could be beneficial to use a composite structure. A tough steel core to withstand bending, with a high surface pressure resistant ceramic coating, could be a suitable option. Such a structure would have a long lifetime in a more industrial application. For a Formula student car, such a structure would probably be too expensive since the whole lifecycle of the car is less than 500 hours of use.

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