Gearbox Project

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Executive Summary

The following report details a VF30 worm drive gearbox, manufactured by Bonfiglioli. The main function of a gearbox is to increase torque. The gearbox has a gear ratio of two, torque range of 24 and frame size of 30. Although it is rather small, it is highly efficient and reliable. The worm

A detailed parts list provides a brief description of each component of the gearbox, its purpose and the material it is manufactured from. The list is divided into major parts, such as the housing, worm wheel and worm shaft, as well as the minor parts such as circlips, spacers, gaskets, seals, caps and screws. This section also discusses whether the parts are VF30 specific or simply off-the-shelf.

Both the Disassembly and Assembly of the gearbox are detailed in the report. These procedures were necessary to further understand and identify the key parts and properties of the gearbox. Pre-assembly/disassembly and post assembly inspections were also completed.

The following section discusses the part relationships. A detailed fits table highlights the type of fit, symbol, and description of fit for each part.

The materials section discusses each material used for the major parts of the gearbox. For the housing, it was found that Aluminium was the best candidate as it has good thermal conductivity and is lightweight and inexpensive. Bronze materials were decided to be best suited for the worm wheel because it is wear-resistant. The worm shaft is commonly manufactured from steel. This is due to its thermal conductivity and hardness.

The manufacturing sequence for each part is then identified. A comparison between Die casting, sand casting and permanent mould casting is completed in order to identify the best process for the housing of the gearbox. The advantages and disadvantages of each processes is listed. Die casting was found of be best suited for the housing as it produces a fine grain structure. This was also then completed for the worm wheel with sand casting, extrusion and forging. Extrusion was found to be most suitable for this part. Forging, cold rolling and extrusion were compared for the worm shaft. The forging process was declared best suited for this component of the gearbox.

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1. Introduction

1.1. Objectives

The following report provides an in-depth analysis into the Bonfiglioli VF30 worm drive gearbox. Gearboxes consist of a series of integrated gears all placed within a housing. Their main purpose is to alter torque while reducing speed [1]. The report will discuss the features and functions of this specific worm drive gearbox followed by a detailed parts list. The assembly and disassembly processes are outlined. This then allows for a qualitative analysis of the materials used within the gearbox as well as the manufacturing process.

1.2. Scope

Features and functions of the gearbox are briefly detailed, outlining the advantages and disadvantages of a worm drive. Minor and major parts are listed with an emphasis on VF30 specific parts. Majority of the report however focuses on the materials and manufacturing process. These two sections of the report are crucial in providing insight into the quality of the gearbox. This then allows for conclusions to be drawn surrounding the most durable, cost-efficient and sustainable materials and manufacturing processes needed to produce this gearbox.

1.3. Process Flow Chart

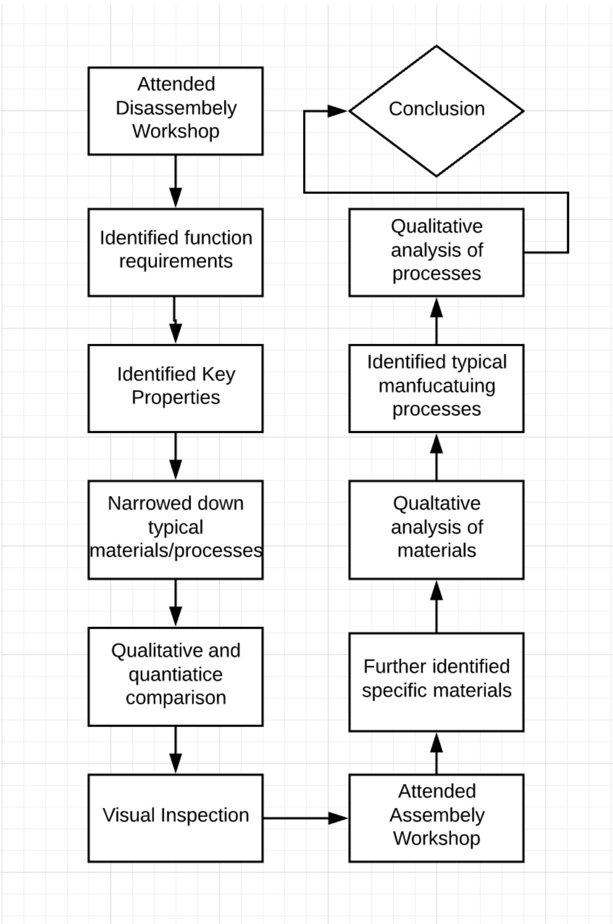


Figure 1: Process Flow Chart

2. Gearbox Overview

2.1. VF30 Worm Drive

The VF30 worm drive gearbox is manufactured by Bonfigioli industrial. This specific model houses a double worm gear, meaning it only moves in one direction. According to Bonfigioli Industries, the key benefits of this gearbox is that it is cost effective, low noise, provides high peak capacity and is highly reliable [2]. Despite the model's compact design, with a frame size of thirty, it has a torque range of 24 Nms, allowing for a significant reduction in speed can still be achieved. The gear ratio refers to the number of turns the output shaft makes when the input shaft turns once [3].

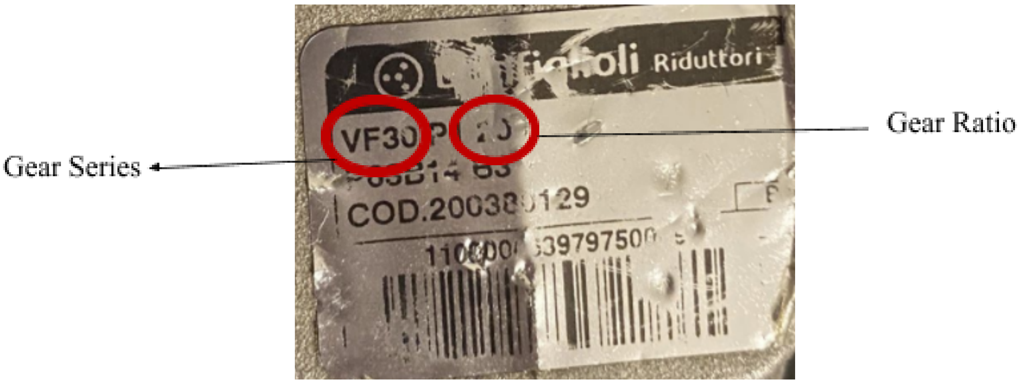


Figure 2: Gearbox number plate

2.2. Features and Functions

Worm gears consist of a spiral (worm shaft), that engages with the worm wheel (a toothed wheel). The reduction ratio is then determined by the number of teeth on the wheel. The worm wheel advances one tooth with each 360º degree turn of the worm shaft. This concludes that the size of the gear ratio is always the size of the worm wheel to 1. The VF30 gearbox has a gear ratio of 20 and therefore, the worm wheel reduces the speed by the ratio 20:1.

The advantage of worm gears is they are able to hold a high reduction ratio with little effort. By simply adding circumference to the wheel, torque is increased. Direction in a worm drive gearbox differs to that in a conventional gearbox as it is not reversible. The direction of power is then also unable to be reserved, unlike other gearboxes where input and output can be changed independently.

The movement in the worm gear is subject to sliding. This is because the worm slides across the tooth of the wheel. The sliding contact, although very quiet, can often produce heat and low transmission efficiency. The spiralling movement can often be problematic as it is susceptible to sliding friction and can then wear. This also lowers efficiency as it causes high heat dissipation. A worm gear has no rolling component to the contact, this results in the worm rubbing the metal of the wheel and potentially rubbing off the lubricant film. Worm gears need a high viscosity lubricant in order to withstand this.

3. Part List

3.1. Major Parts

3.1.1. Housing (includes footing)

Housing of the gearbox is an essential component as it is the assembly surrounding all the internal mechanical parts of the gear transmission. The cover is bolted to the housing, covering the opening that is used to access all the internal components of the gearbox such as the gears and shafts. The housing allows room for lubrication and cooling of the parts. It is important the housing is strong enough to hold all the internal and rotating parts within it. The housing must be made out of material that has thermal conductivity and holds high tensile strength. It is generally manufactured from grey cast iron or cast aluminium as they are found to be the most suitable.

3.1.2. Worm Wheel (includes wheel shaft)

The rotation of the worm turns the worm gear as well as the output shaft. For every rotation of the worm, the worm gear rotates by one tooth. This slows down the motor's output speed and increases torque. The output shaft is the component responsible for delivering power out of the gearbox. This part is a major part specific to the VF30 gearbox. Bronze materials are typically best used for worm gears, as it is wear-resistant and has a low friction coefficient.

3.1.3. Worm Shaft

The worm shaft is the also known as the input shaft does the opposite of the output shaft and delivers power into the gearbox. This component consists of continues spiral thread. When rotating, the worm shaft rotates the worm wheel around its axis. This part is often made out of Steel as it has good thermal conductivity and is a high tensile metal.

3.2. Minor Parts

3.2.1. Circlips

Circlips are thing metal rings that are flexible and shaped as a 'C'. They are integral component of many modern engineering designs as they serve to grasp elements onto a shaft. They fit into a groove inside a o a bore and act as a load-bearing shoulder that holds the parts and prevents them from moving axially. They are made from high tensile steel, forged with hydraulic press and are light and flexible. The VF30 gearbox utilises three different sized circlips, one external 9xm circlip, and two internal circlip, one 32mm, the other 34mm.

Figure 6: Circlips

3.2.2. Spacers

Spacers are generally used to separate two parts and fill in a gap. They can vary in size and diameters and are often flat and cylindrical shaped. The design and size depend on the space it is required to fill. Similar to circlips, they are often made from steel via hydraulic press. Only one spacer is used in the gearbox and is placed between the bearing of the worm shaft and the external circlip.

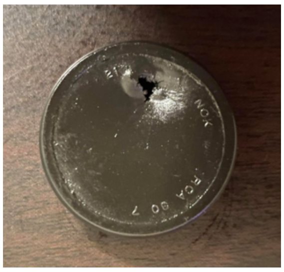
3.2.3. Gaskets

This gearbox uses a total of two gaskets that are used to seal a junction between two mating surfaces. It is a rubber ring, used to prevent any leakages and restrict the entrance of foreign particles. They are made from a soft polymer material, however, can often be made out of metal for heavy machinery. The gaskets used for gearbox as simply made from a flexible graphite tight seal, this is to ensure they are able to form and fill in space.

3.2.4. Seals

A total of two seals are used in the VF30 gearbox. They serve the purpose of blocking oil between the stationary and rotating components of the gearbox. They work to contain oil and restrict contaminants. They are made of soft polymer materials such as rubber, in order to allow for compressibility.

3.2.5. Cap



End caps are used to seal the gearbox housing. The purpose of an endcap is to ensure that that the shaft of the gearbox does not protrude. They are commonly made from a rubber covering as this allows them to stretch and seal around the shaft.

3.2.6. Screws

The gearbox uses a total of eight M5 x 16 bolts. The purpose of bolts is to assemble components together. Four are used on each side of the housing footing and are bolted into the main housing and keeping all the components pact together. These bolts are fairly generic and can be found commercially in a range of shapes and sizes.

4. Disassemble and Assembly

4.1. Disassembly Procedure

The VF30 worm drive is an assembled product to ensure the continual efficiency of the system through proper maintenance and assembly. Allowing the system to be dismantled to check for possible failures/faults and lubrication of the worm drive. Consequently, replacing insufficient parts and oil, repairing the worm drive. The amount of care while disassembling, especially when assembling can make the difference between a long trouble-free gearbox to an instantaneous failure [4]. Therefore, the assembly and disassembly procedure are significant and will be step through to ensure a trouble-free and efficient system. The assembly and disassembly of the VF30 can be carried out by anyone who has the necessary facilities and tools and should be done regularly.

Furthermore, certain safety considerations must be addressed. Significant forces are required to fit and dismantle the worm drive's parts. Specific pressing machines like the arbour press must be used carefully. The arbour press must not be released until it reaches it home position. When pressing with the tools make sure to precisely align them, so the force is translated properly down into the arbour, reducing the likelihood of parts scattering and flinging away. Similarly, remove the seals sensibly to avoid accidents where tools or the seals fly away. Safety glasses and enclosed footwear must be worn for protection. The assembly and disassembly process require specific tools such as external circlip pliers, internal circlip pliers, 4mm Allen key, arbour press, screwdriver, soft Hammer and large Screwdriver seen below in figure 4.0.1. Also, a variety of arbour press tools seen in figure 4.0.2.

4.1.1. Pre-disassembly Inspection

An inspection of the worm drive is necessary to determine the need of maintenance and disassembly. This could be approached by running the worm drive, checking the efficiency of the system. Unnecessarily elevated levels of noise and vibrations may indicate an internal problem, overall effecting the efficiency of the system dissipating unnecessary energy. In addition, the worm drive may evidently be struggling to perform, or might not work. These checks will help reveal an internal problem, requiring the dismantlement of the worm drive and maintenance.

4.1.2. Disassembly Procedure

The oil must be drained. VF30's with a boss feature allows easy oil drainage by drilling a bore through the boss applying a seal to stop. Other VF30's requires the cap seal to be removed and flipped to drain oil. The cap seal (5) was removed by carefully digging a smaller screwdriver underneath the cap, levering the cap with generous force. Do not scratch the seal wall, this will affect its ability to seal. When disassembling the worm drive make sure to carefully looked at each sub-assembly and individual part to identify potential faults and misalignments causing internal problems thereby repairing them. Especially, making sure bearings can freely rotate, by spinning the bearings or connected moving parts. Also, place the disassembled parts on a clean surface or bag to avoid losing and damaging the parts. The 8 m5 screws (16) located on the sides of the housing body were removed using the 4mm Allen key. A soft hammer was used to knock out one of the cover plates (2) from the worm shaft (9) disconnecting the cover plates from the housing body (1). The 2 gaskets (3) must be removed from in-between the cover plate and housing body. The threading and alignment of the worm gear must be checked. The shoulder of the worm gear (7) should be correctly centred and should sit on the shoulder of the housing body. Misalignment can cause unnecessary energy losses, and additional wear out on the worm gear. A worn-out worm gear calls for an immediate replacement.

The internal circlip (15) used to secure the worm thread (8) and input bearing (12) inserted within the groove towards the end of the housing body (1), was removed using the internal circlip pliers. When using the circlip pliers apply just enough force to open and close the circlips, anymore can damage and snap the actual circlips. The worm thread (8) was removed, by mounting the housing body on tool 7 with the end facing downwards and pressed out with tool 11. Again, the worm thread must be carefully looked at to ensure an efficient system, an insufficient worm thread calls for an immediate replacement. The seal (6) located at the back of the housing body was removed by levering a large screwdriver with significant force. The seal must be replaced upon assembly. The internal circlip (14) used to secure the internal bearing (11) located at the back of the housing body was removed with the internal circlip pliers. The external circlip (13) and washer (4) used to secure the input bearing located on the worm thread was removed with external circlip pliers and the washer by hand. The input bearing (11) was pressed out using tool 11, mounting the shaft onto tool 5. The 2 bearings (17) attached to the worm gear was removed by mounting the cover plate onto tool 1 and was pressed out by inverting tool 10. The 2 lip seals (10) were removed from each cover plate, by mounting the cover plate onto tool 1 and was pressed out using tool 2.

4.2. Assembly Procedure

4.2.1. Pre-assembly Inspection

Before assembly it's imperative that faulty parts are identified and replaced/repaired, some examples will be listed for parts and its exclusive damages. The worm gear commonly requires replacement due to the high amounts of torque, friction and energy generated by the system causes teeth wear out. Similarly, the worm thread may be commonly replaced, as it is under the same circumstances as the worm gear. Circlips may snap from forces generate by the system, requiring replacement. Lip seals are continually replaced, to ensure the system is properly sealed. Bearings are also replaced commonly every 5 years for an efficient system. In addition, all parts must be cleaned and oiled before assembly.

4.2.2. Assembly Procedure

Firstly, the input flange bearing (11) was slide down into the back of the gearbox housing body (1). The larger internal circlip pliers were used to insert an internal circlip (15) into the housing groove located above the bearing, securing the bearing whilst confirming free rotation. Secondly, the input bearing (12) was fitted onto the lead-in of the worm thread (8), using the arbour press with tool 9 to fit the the bearing onto the 30micron step. Once fitted the washer (4) was placed on top of the bearing. Using the external circlip pliers to insert a small external circlip (13) in the groove of the shaft securing the washer and bearing in place, again assuring rotation of the bearing. Thirdly, the assembled worm thread was inserted into the back of the housing body and press to fit with the arbour using tool 10. Using the internal pliers, a circlip (14) was inserted in the groove in the back of the housing. Making sure that the worm drive can freely spin. Fourthly, the gear bearing (17), and the cover plate (2) were arbour pressed together using tool 8, its important to note that they should be parallel with each other when pressing to ensure accurate alignment. This was repeated for the remaining cover plate. Fifthly, the cover plate was mounted onto the lead in of the worm gear (7&9) using the arbour with tool 5. Making sure it is seated properly onto the shoulder. Sixthly, the mounted cover plate (2) and worm gear (7&9) was taken and aligned with the housing body, making sure the gears mesh correctly. If the shaft is misaligned it will wear the worm gear quicker. Tool 8 was placed underneath the cover plate/worm drive and housing body, respectively in that order, and pressed through with tool 5. Seventhly, the 8 m5 (16) screws were loosely tightened into the holes of the cover plate with a 4mm Allen key, tighten once all screws were in to ensure correct alignment of the cover plate. The screws are coated in a layer of Loctite to overcome vibrational forces releasing the screws. Screws which don't have an identifiable layer of Loctite, require a recoating. Eighthly, the lip seal (2) was pushed to start with into the housing body, the body was mounted onto the arbour with tool 7 underneath and pressed through with tool 3 to press the lip seal into the housing with the arbour. Lastly, oil was added through the rear of the housing for lubrication, and the cap seal (5) was inserted into the back of the housing and pressed in with tool 3.

4.2.3. Post Assembly Inspection and Ongoing Servicing

Once assembled to ensure good operation, run the worm drive under varying speeds to check for internal problems. If it is evident that the worm drive is working sub optimally, the gearbox must be dismantled to make ensure proper alignment and rotation of all parts along with correct interactions with gear meshing. Within the initial assembly all insufficient parts must be identified and replaced along with oil. If no progress is made by fixing assembly mistakes, the disassembly procedure must be refollowed to reidentified potential failures. Overall, the system should run optimally to ensure the trouble-free gearbox further ongoing servicing is required, such as oil replacement and part replacement. Generally, oil should be replaced within every 1000 hours of operation or 6 months, depending on several factors, which include operating temperature, environment, conditions and type of oil [5]

5. Part Relationships

5.1. Housing Sub-assembly

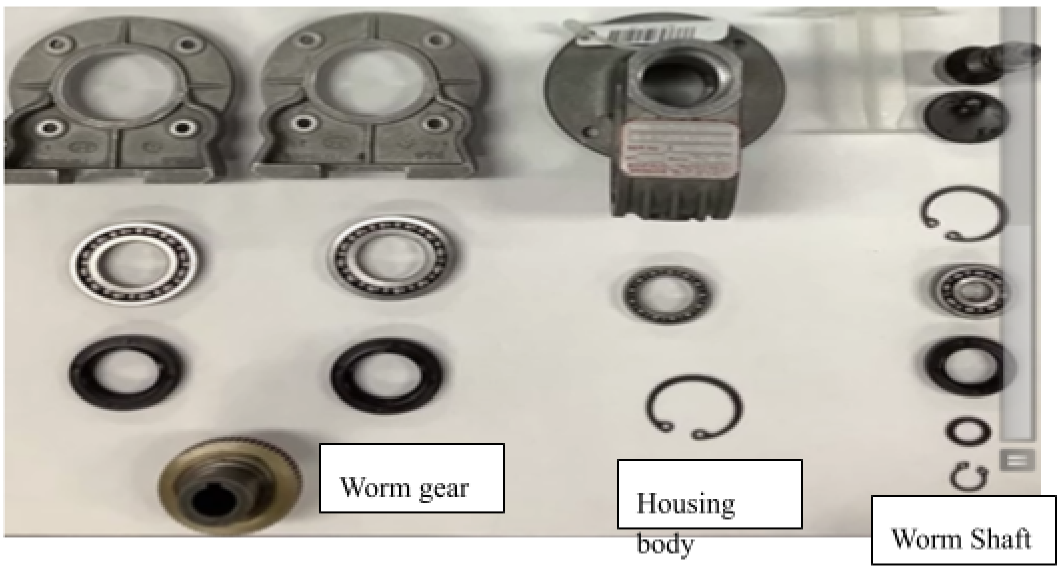


Figure 12: Parts

Parts relationships mainly refer to the interactions of the sub-assemblies, and part fitment. It's important to clarify the interactions and arrangement of the sub-assemblies, to gain better understanding of the worm drive. The three main sub-assemblies are the housing body, output shaft and input shaft shown in figure 12.

5.1.1. Parts

The parts which form the housing sub-assembly are the housing body (1), input flange bearing (11) and the large internal circlip (15).

5.1.2. Arrangement

The input flange bearing slides in the back of the housing body and is secured with an internal circlip. This allows the worm shaft to be inserted in the other end, securing the worm shaft better while allowing free rotation.

5.1.3. Fitment

A sliding fit is used for the bearing inside the housing body, as it is intended to rotate freely while being secured by a circlip which is a location clearance fit.

5.2. Worm Wheel Sub-assembly

5.2.1. Parts

The parts which form the worm wheel sub-assembly are the worm gear (7&9), two cover plates (2), gaskets (3), bearings (17) and lip seals (10).

5.2.2. Arrangement

The two bearings are pressed into the respective holes of the cover plates. The two gaskets are placed in between the cover plate and housing body. One cover plate is pressed onto one side of the worm gear's shaft. Meshing it with the worm thread and fitting the other cover plate. This allows the worm gear to be aligned properly with the worm thread while being secured and able to rotate with no slips.

5.2.3. Fitment

A location fit is initially used for locating the bearing in its place providing a near zero tolerance. Then an interference transition fit is used to secure the bearings into the cover plate. Also, used to insert the bearings onto the worm gear required as it had a 30-micron step from its lead in for a tight assembly, so that there are no slips between the actual bearing and shaft. While, the gasket uses a location fit.

5.3. Worm Shaft Sub-assembly

5.3.1. Parts

The parts which form the worm shaft sub-assembly are the worm thread (8), cap seal (5), internal circlip (14), input bearing (12), washer (4) and external circlip (13).

5.3.2. Arrangement

The input bearing is pressed onto the worm thread and secured with a washer and external circlip inserted into a groove near the end of the worm thread. The worm thread is then pressed into the housing body, with an internal circlip above in the housing component to secure the worm thread. This arrangement allows the worm thread to freely rotate being connected to input bearing with a washer and the bearing located in the housing body. Whilst locking down the washer and input bearing with an external circlip and being further secured to counter the lateral forces of the worm drive by an internal circlip.

5.3.3. Fitment

An interference transition fit is used on the input bearing, as it is tightly assembled with a lead in located along the worm thread. A sliding fit is used for the washer, while requiring a location clearance fit for both circlips.

5.4. Fits Table

Parts		Type of Fit	Symbol	Type of fit	Description
Bearings (17)	Cover Plate (2)	Transition	H7/k6	Location Fit	This fit provides a zero-tolerance fit, allowing for precise location of parts. The bearing requires a location fit into the cover plate. Thus, a location was used initially to locate the bearing.
Internal Circlip (15)	Housing Body (1)	Clearance	H7/g6	Location Clearance Fit	This fit provides a snug fit for location of stationary parts. The circlip is used to secure the bearing and worm thread. Therefore, requiring a stationary fit.
Worm shaft (9)	Bearings (17)	Transition	H7/n6	Interference Transition Fit	This fit is used for tight assembles allowing turning moments to be transmitted without slippage. The worm shaft and bearings must be tightly fitted to ensure no slippage. Thus, interference transition fit is most suitable.
Bearing (11)	Housing Body (1)	Clearance	H7/g6	Sliding Fit	This fit allows parts to move and turn freely whilst being secure. The bearing inside of the housing body requires complete rotation for the worm thread. Accordingly, a sliding fit is most suitable.
Input Bearing (12)	Worm Thread (8)	Transition	H7/n6	Interference Transition Fit	This fit is used for tight assemblies to prevent slippage transmitted from turning moment. This was used as the bearing and worm thread must not slip.

Table 1

6. Materials

The major parts considered in this section of the report will be the housing, including the footing, the worm shaft, and the worm wheel. Besides the gaskets these are the only specifically manufactured parts for this gearbox. For the context of the report the output shaft and input shaft will be considered the same material, and therefore only the gear section for the output shaft will be analysed. The design and quality of the materials of the worm drive are crucial to an acceptable and reliable service life.

6.1. Housing

6.1.1. Function and Required Properties

The housing of the Bonfiglioli Worm Drive Gearbox is used to maintain the alignment of all the pieces, as well as transferring heat produced in the product. It provides mechanical support for the elements inside the gearbox, as well as a protection from outside factors. The housing must also help contain lubrication. The housing must conform to several different mechanical properties to be applicable, but also there are physical, as well as practicality properties which are considered in the refinement of material selection.

Material selection for the housing is primarily reliant on the materials manufacturability, cost and mechanical properties. The gearbox casing is a single piece casting, which needs to be precisely machined in order to correctly align and maintain the shape of the internal elements. Ideally the housing would also be lightweight and have a high tensile strength.

Relevant properties for the worm drive housing would include:

- Thermal conductivity
- Mechanical integrity
    - Strength
    - Hardness
    - Fatigue
    - Tensile strength
- Machinability
-

6.1.2. Candidate Materials

Material	Thermal conductivity	Shear Strength	Hardness	Fatigue	Machinability	Tensile strength	Density
Aluminium casting alloy	135W/m-K	165MPa	62.5 RB	115MPa	57.9%	244MPa	2.73g/cc
Grey Cast iron	26.6 W/m-K	545MPa	69.3RB	260MPa	39%	310MPa	7.22g/cc
Medium Carbon steels	47.7 W/m-K		94.8RB	370MPa	60.1%	987MPa	7.85g/cc

Table 2

Of the compared candidate materials, Aluminium has good thermal conductivity but has less strength than other materials. Aluminium is lightweight, inexpensive and easily cast and machined in comparison.

Cast irons are stronger but aren’t as good thermal conductors. They are harder to machine, heavier and don’t possess much greater hardness. They could be used in a higher stress situation for greater strength. Steels are harder to cast but are more machinable. They are better thermal conductors than a cast iron, but not as good as aluminium.

6.1.3. Material Identification

The most important properties for the gearbox will be its thermal conductivity, cast ability and machinability. All the above materials have respectable qualities for the application; however, aluminium is the most common material used in this application. Aluminium alloys are used for their excellent thermal conductivity, good machinability, and low melting temperatures for casting. Worm drive gearboxes typically do operate at a slightly higher temperature than other gearing types, however these temperatures are far below melting temperatures for the candidate materials. Aluminium is also a far less dense than other candidate materials, meaning the assembly will be lightweight. Aluminium also has a respectable strength value, a decent fatigue strength for its application, as well as a good hardness. It is likely the material has taken on some form of heat treatment to further increase the hardness, and overall applicability for the role.

6.2. Worm Wheel

The output shaft comprises of two materials, the gear and the shaft. This section will analyse only the gear section, and the output shaft section will be assumed to be the same material as the input shaft

6.2.1. Function and required properties

The Worm Gear is a crucial part of the VF30 worm drive box. The wheel is loaded through the spiralling motion of the worm shaft. It is responsible for the transmission of power out of the gearbox. The material must be a castable and machinable material, to allow for precise machining giving an efficient power transmission through the worm gearing setup. The material must be able to withstand the pressure applied from the high torque loads of a worm gear setup. The material should be selected with a range of considerations in different areas including mechanical, economical and manufacturability.

The worm gear system has an inherent resistance to tooth breakage [4], and often heat and wear are the principle factors for consideration when choosing a gear and worm setup. Primary stresses include rolling and rubbing stresses, as well as a reverse bending stress on separation [4]. There is no universal wear test that can be given, however metals with a higher hardness tend to resist wear better. For the worm gear setup, the worm shaft is typically the harder metal of the pairing, and the gear a softer metal. This is important due to the worm shaft receiving many more stress cycles than the gear. Ideally the worm gear will be a hard material, with good strength, toughness and weight. From inspection of the part, the gear is cast onto the output shaft, and therefor will need to be a castable, machinable material, that can take on heat treatment.

6.2.2. Candidate Materials

Bronze materials are typically used for worm gears, for their wear resistance, and low coefficient of friction on the harder worm input shaft. Several bronze alloys will be considered for the worm gear selection. An Aluminium bronze alloy, a phosphor bronze alloy, a manganese bronze, and a free cutting brass. The aluminium alloy analysed will be an 8% aluminium alloy, and values for a O60 soft annealed product. Machinability is compared against a Free-Cutting brass.

Material	Hardness (Brinell)	Ultimate Tensile strength	Machineability	Density	Castability	Thermal conductivity (W/m-K)
Aluminium Bronze (C61000)	100*	480MPa	20%	7.78g/cc	no	69

Phosphor bronze (C90700)	102	240MPa	20%	8.78g/cc	yes	70.6
Manganese bronze (C86100)	180	655MPa	30%	7.9 g/cc	yes	35
Free cutting brass (C36000)	-	338 - 469MPa	100%	8.49g/cc	No	115

Table 3

* Converted from a different hardness test value

The material required must be resistant to the wear on the system. Each of the analysed bronzes have a strong tensile strength, and good hardness, making them acceptable for the role. The analysed brass has excellent machinability, and good thermal conductivity, however it is a wrought material, and therefore not cast, and likely inapplicable for the gear.

6.2.3. Material Identification

Phosphor bronze was the selected material for the VF30 gearbox. The material, despite not being the hardest or strongest of the candidate materials, it is a castable, a strong thermal conductor. Bronzes were chosen not only for their relative softness, but also their low experimental coefficient of friction. Phosphor Bronze on steel in a dry unlubricated environment has a coefficient of 0.35, whereas steel on steel has a coefficient between 0.5 – 0.8 [4]. This can increase the life of both the worm drive and worm gear, as sliding and rubbing are the main form of power transmission in the system. A C90700 bronze is the best choice for heavily stressed worm gear applications [6]. The part is centrifugally cast onto the output worm shaft, which is important for the reliability of the output shaft as an assembly.

From a visual inspection of the part, it's clear the material is a copper alloy, either a bronze or a brass. Brass is often used for gearing parts, however the frictional coefficient for a brass on steel, in a dry unlubricated environment is 0.51, significantly higher than that of the Phosphor Bronze [4]. This will make brasses a less appealing choice for the worm gear.

6.3. Worm Shaft

6.3.1. Function and required properties

The worm shaft provides the input to the worm gear. It is important this material is a strong and tough material, that can be machined to a high standard. The accuracy of the machining of the worm shaft is important in maintaining system efficiency. The worm shaft will also come under many more stress cycles than the worm gear, and thus is important for the input shaft to be of a strong and hard material in order to resist wear on the system. The material should be heat treatable for increased strength.

Properties important to the performance of the input shaft are:

- Hardness
- Tensile strength
- Machinability
- Thermal conductivity
- Hardening capability

6.3.2. candidate Materials

Typical materials found in worm drive gearboxes include a range of steels not limited to; high nickel steels (AISI 4320,9310), medium carbon steels at ~0.5% carbon (AISI 1040) and for the sake of comparison a soft cast iron.

Material	Hardness Brinell	Tensile strength	Machinability	Thermal conductivity	Hardening capability
4320 Steel	235	793MPa	60%	44.5W/m-K	yes
1040 steel	170	595Mpa	60%	51.9W/m-K	yes
Cast iron	294	479MPA	~40%	26.6W/m-K	yes
420 Stainless steel	594	2025MPa	30%	24.9W/m-K	yes

Table 4: Comparison of candidate worm input shaft materials

The 4320 steel is a commonly used part for the worm input drive. It has good thermal conductivity, is one of the stronger candidate materials, and has good hardness. The steel also responds well to heat treatment for strength. The 420 Stainless steel is the hardest, and strongest of the candidates and would best suit high load environments and have strong corrosion resistance due to the 12% chromium. Medium carbon steels such as the 1040 steels, despite having respectable attributes for the worm drive are subject to surface cracks when grinding the thread during the manufacturing process [6].

6.3.3.

For the worm drive in the VF30, the most applicable option for overall strength and hardness will be the 420 Stainless steel. This steel, although not the most machinable steel will provide strength and hardness. The steel is also able to be case hardened, which will be an important part of reaching the strength and hardness capabilities for manufacturing. From visual inspection of the VF30 box, the worm is made of a steel.

7. Manufacturing

7.1. Housing

7.1.1. Candidate Manufacturing Processes

The quality of the housing is heavily dependent on the manufacturing processes involved. Due to the shape of the gear box housing, the component can not be made through bulk deformation and therefore the material is casted. Typical manufacturing processes for the housing include; die casting, sand casting and permanent mould casting. A quantitative analysis of these manufacturing processes can be seen in Table 5.

Table 5: Qualitative analysis of manufacturing processes for the housing of the gearbox

Process	Advantages	Disadvantages
Die Casting (Kopeliovich, 2012)	• Thin walls and intricate shapes are able to be cast with fine detail. • Very good surface finish and high accuracy in dimensions. • Fine grain structure results in good mechanical properties (e.g. hardness and tensile strength). • Able to produce parts at a high rate. • Low labour cost. • Scrap is recyclable.	• Trimming is required. • High tooling and equipment cost. • Long lead time.
Sand Casting (Engineering Product Design, 2017)	• Low tooling and equipment cost. • Wider range of materials are castable. • Short lead time.	• Coarse grain structure results in poor mechanical properties. • Rough surface finish (will require secondary processes). • Limitations in the complexity of the shape and wall thickness. • High machining tolerances and poor dimensional accuracy. • Defects such as porosity and shrinkage are unavoidable.
Permanent Mould Casting (Kopeliovich, 2012)	• Good surface finish and high dimensional accuracy. • Complex shapes and designs are castable. • Homogeneous grain structure. • Low labour cost and scrap is recyclable. • Quick solidification of the material results in better mechanical properties. • Low porosity and low shrinkage.	• Limitations in casting of high melting point metals into metallic moulds. • Short mould life and high tooling cost. • Long lead time. • High tooling and equipment cost.

7.1.2. Identification of Manufacturing Process

The main purpose of the housing for the gearbox is to provide protection for the internal components. This suggests that it is ideal to have a housing of high strength. From the analysis in the previous section, it was determined that die casting would be the most appropriate form of process for the bulk shape forming of the component. Die casting produces a fine grain structure within the material which results in better mechanical properties such as increases in hardness and tensile strength of the component.

Due to the high melting point of the selected material, it was necessary to choose cold-chamber die casting over hot-chamber die casting (Premier Die Casting Company, 2016). Machining components of the process can be seen in Figure 13. The steps involved in cold-chamber die casting include:

1. With the die closed, a sufficient volume of molten metal is poured into the shot sleeve with the use of a ladle.
2. The molten metal is then injected into the die cavity through the use of a high pressure hydraulic plunger and held there until solidification.
3. Once the metal has solidified, the die will open with the plunger advancing to ensure the casting remains positioned in the ejector die.
4. Finally, the plunger will retract and he ejector pins will then push the casting out of the die (Dynacast, 2019).

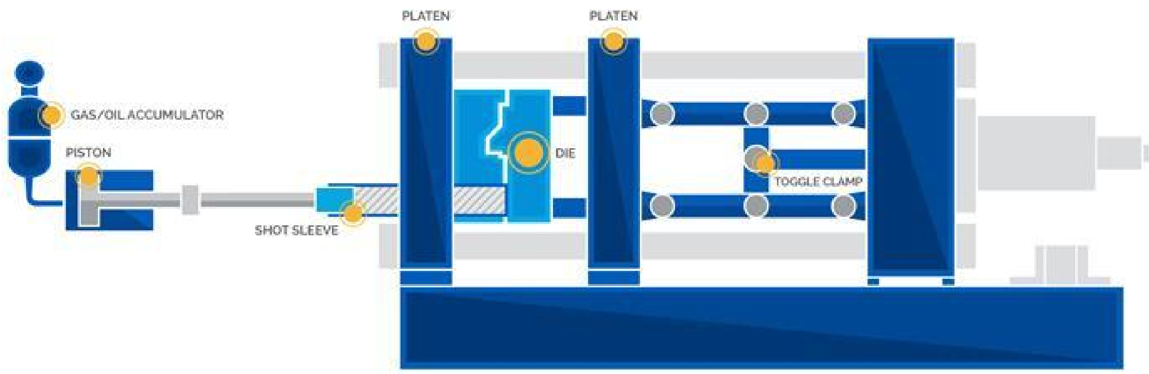


Figure 13: Main components of a cold-chamber die casting machine (Dynasty, 2019)

With the bulk shape of the housing formed through casting, finishing processes are then used to improve the quality of the component. Mechanical deburring and vibratory deburring are done to smooth surfaces, remove loose flash and round sharp edges. Another secondary process may include anodizing to increase the housing's durability and corrosion resistance (Dynacast, 2019).

7.1.3. Manufacturability of Material

The selected material, aluminium alloy, is relatively easy to cast. However, a cold chamber machine is required due to its relatively high melting point (Premier Die Casting Company, 2016). Therefore, the housing will be processed though cold-chamber die casting which is suitable for casting an aluminium alloy.

7.2. Worm Wheel

7.2.1. Candidate Manufacturing Process

The worm wheel has a basic cylindrical shape that can be easily manufactured through many different processes. Table 6 shows the typical manufacturing processes of the worm wheel and a quantitative analysis of these processes.

Table 6: Qualitative analysis of manufacturing processes for the worm wheel

Process	Advantages	Disadvantages
Sand Casting (Engineering Product Design, 2017)	• Low tooling and equipment cost. • Wider range of materials are castable. • Short lead time.	• Coarse grain structure results in poor mechanical properties. • Rough surface finish (will require secondary processes). • Limitations in the complexity of the shape and wall thickness. • High machining tolerances and poor dimensional accuracy. • Defects such as porosity and shrinkage are unavoidable.
Extrusion (Paul Murphy Plastics, 2019)	• Capable of a high extrusion ratio (billet cross-sectional area to extruded part cross-sectional area). • Cold extrusion can achieve high mechanical properties. • The basic cylindrical shape of the worm wheel can be extruded. • Wide range of materials can be extruded including brittle materials. • High production rate.	• High tooling and equipment cost. • Limitation in complex shapes.
Forging (Club Technical, 2019)	• Longitudinal grain flow structure improves mechanical properties (better fatigue properties and increase in strength). • Broad size range of products and great design flexibility. • Less machining required as the product will be much closer to the near-net-shape. • More efficient use of raw materials.	• Capital cost is high.

7.2.2. Identification of Manufacturing Process

Due to the selection of phosphor bronze as the material for the worm wheel, the most suitable manufacturing process is extrusion. The material is forced through a die of relatively similar size to the desired size of the worm gear. The extruded part can then be cut to a desired width of the worm wheel as shown in Figure 14a.

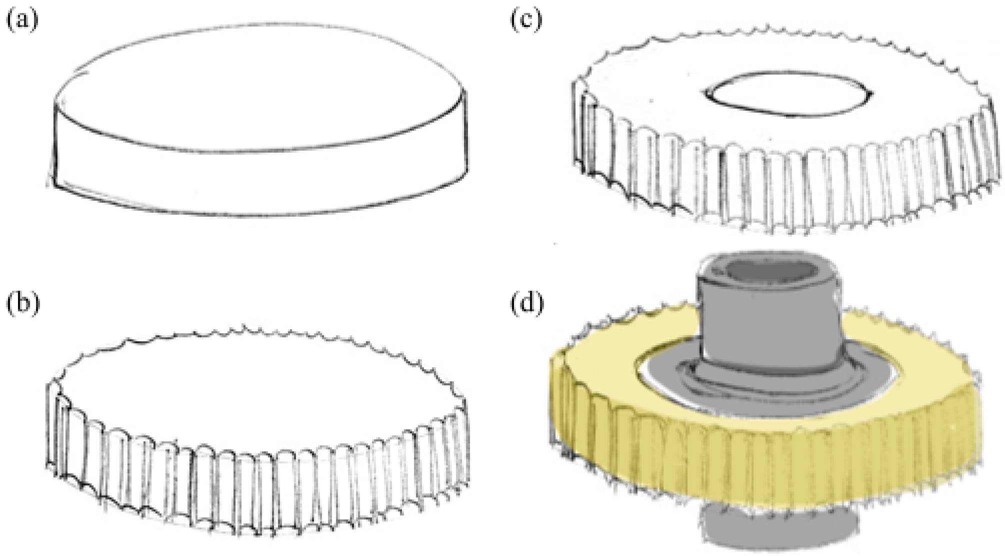


Figure 14: Manufacturing process of a worm wheel; (a) bulk deformation, (b) formation of gear teeth, (c) boring of worm wheel, and (d) output shaft inside worm wheel

Machining processes are then used to give the worm wheel its shape. This starts by turning the component precisely to the desired size. A computer controlled gear hobber is then used to cut into the worm wheel forming teeth. The cuts will gradually increase in depth to a specified depth to avoid chipping the cutting blades. Figure 14b shows the formed teeth of the worm wheel.

The worm wheel is then drilled into to create room for the output shaft through the machining process of boring. This process is illustrated in Figures 14c and 14d.

The worm wheel will then go through finishing processes. Grinding is done to get the gear to precise sizes. In addition, honing is done to improve the geometric form of the surface as well as improving its surface finish (Srivastava, 2016).

7.2.3. Manufacturability of Material

The selected material of phosphor bronze was considered when choosing the manufacturing processes of the worm wheel. Phosphor bronze is able to be extruded into the near-net-shape of the worm wheel. In addition, the material is also able to be cut and grinded during the machining and finishing processes of the manufacturing. Therefore, the selected material is able to be manufactured into a worm wheel through the specified manufacturing processes.

7.3. Worm Shaft

7.3.1. Candidate Manufacturing Process

A quantitative analysis of some typical manufacturing processes of a worm shaft are presented in the table below.

Table 7: Qualitative analysis of manufacturing processes for the worm shaft

Process	Advantages	Disadvantages
Forging (Club Technical, 2019)	• Longitudinal grain flow structure improves mechanical properties	• Capital cost is high.

	(better fatigue properties and increase in strength). • Broad size range of products and great design flexibility. • Less machining required as the product will be much closer to the near-net-shape. • More efficient use of raw materials. • High rate of production.	
Cold Rolling (Monroe, 2019)	• Wide range of shapes are able to be produced. • Good surface finish and high dimensional accuracy. • High rate of production. • Short lead time.	• Possible defects include; centre cracks and edge cracks. • High equipment and tooling cost. • Limitation in the shape of the component.
Extrusion (Paul Murphy Plastics, 2019)	• Capable of a high extrusion ratio (billet cross-sectional area to extruded part cross-sectional area). • Cold extrusion can achieve high mechanical properties. • The basic cylindrical shape of the worm wheel can be extruded. • Wide range of materials can be extruded including brittle materials. • High production rate.	• High tooling and equipment cost. • Limitation in complex shapes.

7.3.2. Identification of Manufacturing Process

From the analysis, it was decided that forging would be the most ideal manufacturing process for the worm shaft. The main reason is because of the longitudinal grain flow structure that follows the contour of the component. This grain flow is ideal for the improvement of mechanical properties of the component. In order to make the required cylindrical shape, the material will undergo progressive open-die forging. The initial shaft of the material is held by a manipulator and is placed under the die to deform the workpiece. The manipulator will rotate the shaft progressively until the shaft is at the desired size (Grillo, 2017). The forged shaft is illustrated in Figure 14a.

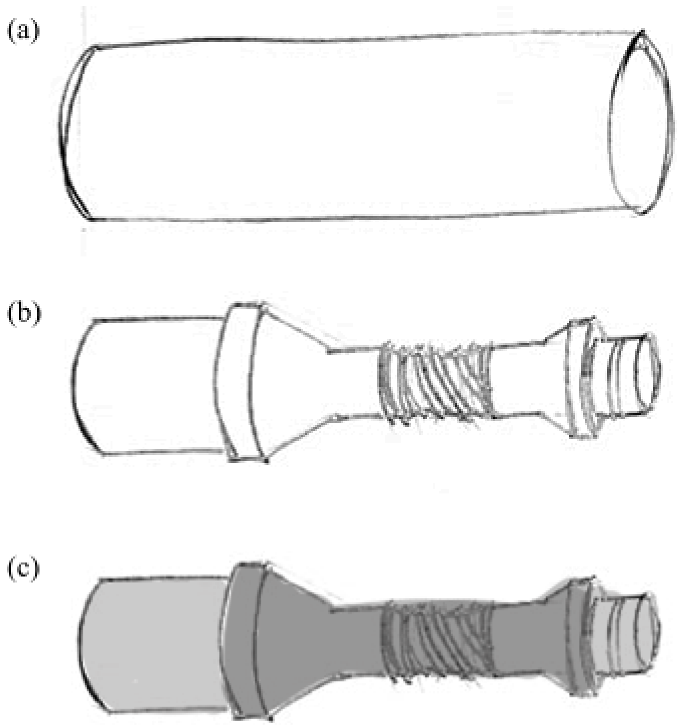


Figure 15: Manufacturing process of worm shaft; (a) forging near-net-shape, (b) turning and hobbing, and (c) case hardening

The cylindrical body is processed through machining processes to get the desired shape of the worm shaft. A possible machining process is turning. This allows the shaft to have different diameters along the pipe in accordance with its desired shape. To get the teeth into the shaft, a machining process such as hobbing is done. Unlike the worm wheel, the teeth for the worm shaft will be slightly angled to produce the rotational motion turning the worm wheel. Figure 15b shows the product of the machining processes.

Case hardening to harden the external layer to endure wear and tear. This is important as the worm shaft will be turning and grinding against the worm wheel. This process involves adding carbon to the outer layer to improve its durability. Figure 15c illustrates the worm shaft after case hardening. The worm shaft will then go through finishing processes. These processes include grinding and honing to get the shaft to the correct sizing and to touch up on the surface finish quality of the worm shaft.

7.3.3. Manufacturability of Material

The selected material, stainless steel, is capable of being forging due to its resistance against corrosion and heat. This allows the stainless steel to be forged into the cylindrical shape close to the shape of the worm shaft. The material is also able to undergo the machining processes of turning and hobbing without any problems. With the surface hardened, the material and manufacturing processes involved in worm shaft provide it with great durability and strength as well as improvements in other mechanical properties.

8. Conclusions

The disassembly and analysis of the Bonfiglioli VF30 worm drive gearbox has provided a thorough understanding of the features and parts required in a worm drive gear setup. The particularity of part fitment and complexity of even a simple gearbox setup such as the VF30 gives a broader insight into the mechanical assemblies that are so crucial to industry. The in-depth analysis of the VF30 gearboxes specific components has highlighted the necessity of engineering design processes. Material selection for the gearbox showed the broad range of available alloys and their strengths and weaknesses for different applications. The materials used in the gearbox proved to also be reliant on the manufacturing processes that would need to take place in order to have an efficient and reliable product, able to withstand the desired properties. In conclusion the analysis of the VF30 has shed light on the importance of engineering processes and design.

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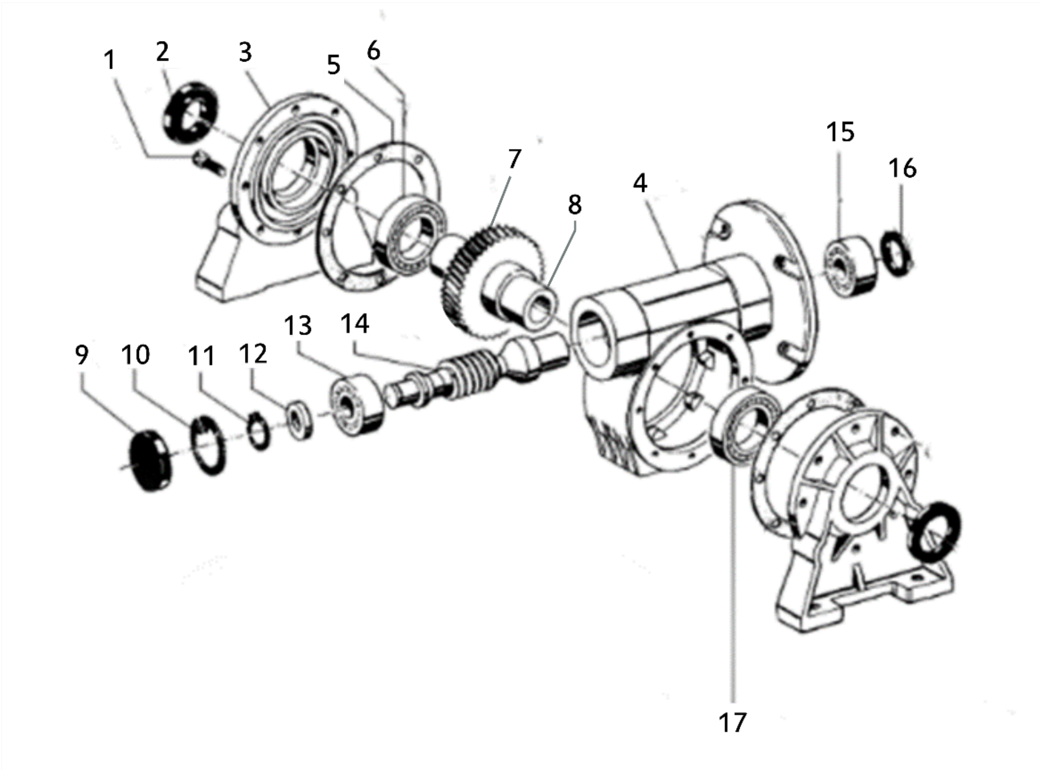
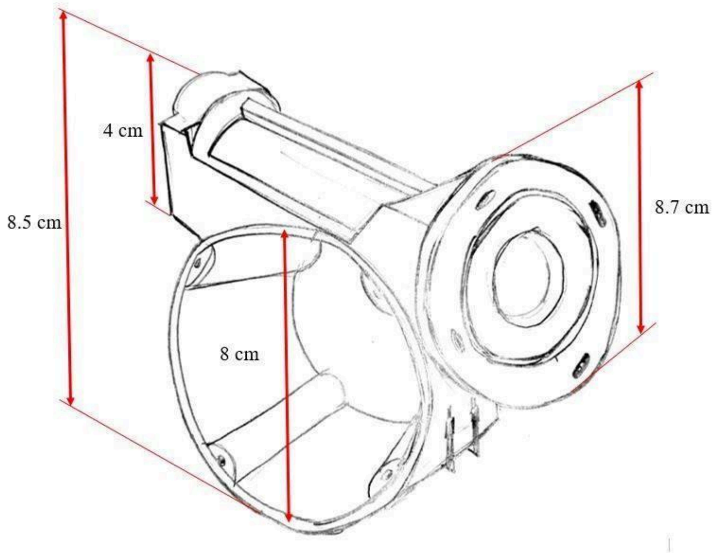
Appendices

Appendix I : Gearbox Part List

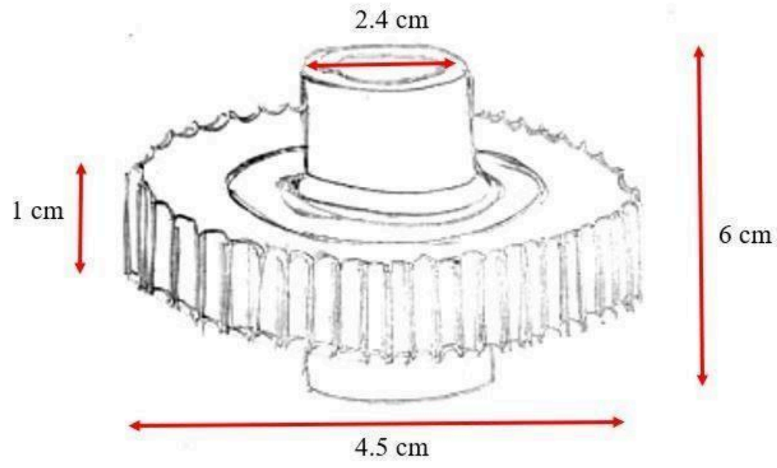


#	Part	#	Part
1	Hex head screw	10	Internal circlip
2	Oil seal (wheel shaft/output shaft)	11	External circlip
3	(a) Housing - footing	12	Spacer
4	(b) Housing - main body	13	Bearing (worm shaft/ input shaft) (non-drive end) (NDE)
5	Gasket	14	Worm shaft (input shaft)
6	Bearing (wheel shaft/output shaft)	15	Bearing (worm shaft/input shaft) (drive end) (DE)
7	(a) Worm wheel	16	Oil seal (worm shaft/input shaft)
8	(b) Wheel shaft (output shaft)	17	Bearing (wheel shaft/output shaft)
9	End cap		

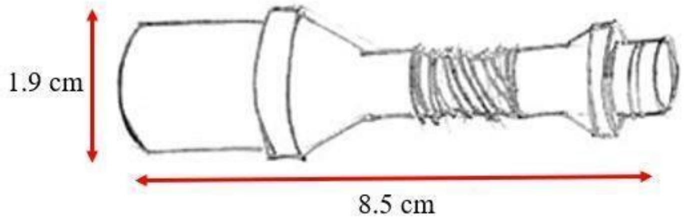
Appendix II. Sketches of Major Components



Appendix I (I) – Gearbox Housing Sketch



Appendix I (II) – Worm Gear



Appendix I (III) – Worm Shaft

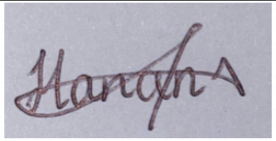
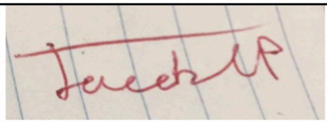
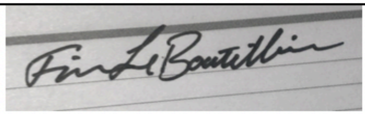
Appendix III. Statement of Contributions

QUEENSLAND UNIVERSITY OF TECHNOLOGY (QUT), SCIENCE AND ENGINEERING FACULTY (SEF)
Engineering Mechanics

Declaration and Statement of Contribution Form

All group members should complete this form. Include this completed form as an Appendix to your group submissions. **Each member is expected contribute equally to the project to receive equal marks. Case-by-case decisions will be made on adjustments to marks, as required.** Any incomplete details should be explained in writing with this form. Each member has the responsibility to avoid plagiarism for their contribution. Individually or team penalties may be imposed for substantiated student misconduct. Please read the Manual of Policies and Procedures on plagiarism and student misconduct.

Project Team Number: WOR_03_004

Full name	Student Number	Description of responsibilities. State in dot points which sections exactly you were responsible for and state any other responsibilities.	Contribution / Moderation Factor (did you perform all tasks required to expected group standard?) e.g. 1 for full contribution, 0.5 for half contribution	Signature
Hanan Abdelrahman	**N10000992**	• Introduction, Gearbox overview, parts list, final edit • Meeting minutes • Executive summary	**1**	
Anthony Ngo	**N10615911**	• Manufacturing section • Sketches of major components	**1**	
Jacob Garcia-Pavy	**N10012478**	• Dissemble and Assembly • Part Relationship • Sketches of major components	**1**	
Finn Leboutillier	**N10263110**	• Materials section • conclusion	**1**	

Appendix IV. Team Charter

GROUP ID	Team Member Names	Student #
	Hanan Abdelrahman	N10000992
	Anthony Ngo	
	Finn Leboutillier	
	Jacob Garcia-pavy	N10263110

1. Meetings
    - What is our consensus about when, where, and how often to have team meetings?
    - What is expected of members with regard to attendance, timeliness, and preparation?
    - Also, what is the balance between work and fun?

Fortnightly Meetings, Friday 11am after lecture.
Meetings were then changed to accommodate for online learning – over zoom.

2. Working
    - What is our goal for this team project?
    - What do we expect from one another about standards?
    - What about meeting deadlines?
    - How equally effort and work should be distributed?
    - How work will be reviewed?
    - What to do if people do not follow through on commitments?

- Clear, respectful communication towards one another
- Time management skills- ensuring you meet deadlines

3. Communication
    - When should communication take place, who is responsible, how should it be done (phone, email, etc.)?
    - How will we discuss feelings about the team or members?
    - By what means will we communicate with one another across different media like phone, e-mail, etc?
    - What is our document control system?

- Communication will mostly take place over our Facebook group chat
- Discuss opinions in confidence whilst being respectful
- All documents will be sent in the group chat, Hanan will then collate them and save them on a file.

4. Leadership
    - How will we decide who takes the leadership role for what aspects of our work?

- What positions will be delegate in the group / what roles will we make?
- What expectations do we have for how those in leadership roles should act?

> - Each member was delegated their task by Hanan.
> - The group has no specific leader, but rather we all contribute and collaborate to complete our set tasks.

5. Considerations
   - How will we treat one another personally while working together?
   - How should minority viewpoints be treated?
   - How do we manage the time during our meetings?
   - What information will we consider to be confidential?)

> - With respect and a professional manner
> - The minority viewpoint will be considered and communicated as to why or why not they are best for team goal

6. Accountability
   - What are the consequences for violating each of the agreements we've established above?
   - Who will decide and how will this be enforced?
   - At what stages do we agree to contact the tutor about any group issues?

> Depending on the circumstance, the violating team member will be spoken to in the group chat and be given a chance to redeem themselves. A tutor will only be contacted if said team member has failed to reply, or complete work within a suitable time frame and only after several warnings/complaints from other team members.

Appendix V. Meeting Minutes

TEAM MEETING AGENDA				
1. *Get to know each other!* 2. *Team Charter* 3. *Agree on weekly meeting time* 4. *Go through gearbox, take proper pictures and look at parts*				
Meeting Details				
Chairperson: Hanan		**Minutes: 45**	**Date & Time: 19/03/2020**	**Location: Library**
Attendees: Anthony, Jacob Finn		**Absent: -**		
	Item	**Notes** **What details are important for attendees?**		
1	**Completed**			
2	**Completed**	Discussed and completed as well as posted in Facebook group chat.		
3	Completed	Fortnightly meetings were seen to be more suitable for the moment as the final report is not due until the end of semester. Next meeting to be held on 02/04/2020		
4	Completed- but not fully	Only briefly discussed the parts, meaning we must continue this next week		

ACTION ITEMS				
#	**Item** **What has to be done by the next meeting**	**Action** **What action is required to get it done?**	**Who:** **Who is responsible?**	**Due:** **When is it due?**
1	Decide which part of report you would be interested in completing	Look over report brief on blackboard	Everyone	By next meeting

TEAM MEETING AGENDA				
The chairperson fills out this form before a meeting to organise tasks to be discussed 1. *Discuss each section of the report* 2. *Decide who is completing which section* 3. *Decide on how meetings/group work is to be conducted now that we have shifted to online learning*				
Meeting Details				
Chairperson: Hanan		**Minutes: 60**	**Date & Time: 23/04/2020**	**Location: zoom**
Attendees: Hanan, Anthony, Finn, Jacob		**Absent:**		
	Item	**Notes** **What details are important for attendees?**		
1	**Completed**	Each section of the report was discussed. Providing all members with a general overview of what is expected in each part.		
2	**Completed**	Each section of the report was split up between the four of us. Each member has approximately the same amount of work to do as one another.		
3	**Completed**	With online learning being fairly new and difficult to navigate, group has decided that we will continue to conduct meetings via zoom and discussions via facebook group chat.		

ACTION ITEMS				
#	**Item** **What has to be done by the next meeting**	**Action** **What action is required to get it done?**	**Who:** **Who is responsible?**	**Due:** **When is it due?**
1	Start drafting section of report	Begin research and further analysis of gearbox	All team members	07/05/2020
2	Understand disassembly of gearbox	Watch gearbox disassembly video that will be posted online	All team members	07/05/2020

<table>
<tr><th colspan="5">TEAM MEETING AGENDA</th></tr>
<tr><td colspan="5">The chairperson fills out this form before a meeting to organise tasks to be discussed
1. Discuss current progress
2. Discuss assembly video
3. Discuss when will be a suitable time to have our individual parts completed</td></tr>
<tr><th colspan="5">Meeting Details</th></tr>
<tr><td colspan="2">Chairperson: Hanan</td><td>Minutes: 60</td><td>Date & Time: 07/05/2020</td><td>Location: zoom meeting</td></tr>
<tr><td colspan="2">Attendees: Anthony, Jacob, Finn</td><td>Absent: -</td><td></td><td></td></tr>
<tr><td></td><td>Item</td><td colspan="3">Notes
What details are important for attendees?</td></tr>
<tr><td>1</td><td>Completed to an acceptable standard</td><td colspan="3">Everyone is drafting their section of the report. No major developments yet.</td></tr>
<tr><td>2</td><td>Completed</td><td colspan="3">All team members have watched the assembly video and briefly discussed it.</td></tr>
<tr><td>3</td><td>Completed</td><td colspan="3">Aim is to complete each section of the report at least 2 days before submission ate. This will allow for editing/formatting of the final report.</td></tr>
</table>

<table>
<tr><th colspan="5">ACTION ITEMS</th></tr>
<tr><td>#</td><td>Item
What has to be done by the next meeting</td><td>Action
What action is required to get it done?</td><td>Who:
Who is responsible?</td><td>Due:
When is it due?</td></tr>
<tr><td>1</td><td>Complete as much of individual sections as possible</td><td>Each member to continue working on their individual part</td><td>Everyone</td><td>-</td></tr>
</table>

TEAM MEETING AGENDA				
The chairperson fills out this form before a meeting to organise tasks to be discussed 1. *Check progress* 2. *Decide on who will be completing sketches for appendices* 3. *Decide when the most suitable time will be for everyone to submit their part* 4. *Decide on who will be formatting/submitting final report*				
Meeting Details				
Chairperson: Hanan		**Minutes: 60**	**Date & Time: 22/05/2020**	**Location: zoom meeting**
Attendees: Anthony, Jacob, Finn		**Absent:**		
	Item	**Notes** **What details are important for attendees?**		
1	**Completed**	Jacob has completed his part and sent it to the group. Remaining group members are still progressing through.		
2	Completed	Jacob will complete the sketches for the appendix.		
3	Completed	Group has decided we will try to send parts by next week Wednesday; however this may be difficult as everyone has a lot of assessment coming up.		
4	Completed	Anthony will send final format to Hanan, who will then put together the final report and submit		

ACTION ITEMS				
#	**Item** **What has to be done by the next meeting**	**Action** **What action is required to get it done?**	**Who:** **Who is responsible?**	**Due:** **When is it due?**
1	Sketches for appendix	Hanan to send measurements of parts to Jacob, so that he can complete the sketches	Hanan, Jacob	28/05/2020
2	Finish Parts	Each group member needs to submit their part to Hanan so she is able to put it together	Everyone	28/05/2020
	Submit Final report	Complete & put together parts	Hanan	29/05/2020