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1.0 Introduction

The target product is a POWAUTO PUKS50R hydraulic gear pump, manufactured by David Brown Hydraulics. It is used where high pressure and large flow is required, such as in cranes, hydraulic presses, aerial platforms, and garbage compactors. The pump size is 65, which has a flow rate of 64 L/min at 1000RPM, and a maximum flow rate of 124 L/min. The operating speed is 600-2000 RPM, and it can produce pressures of up to 28MPa.

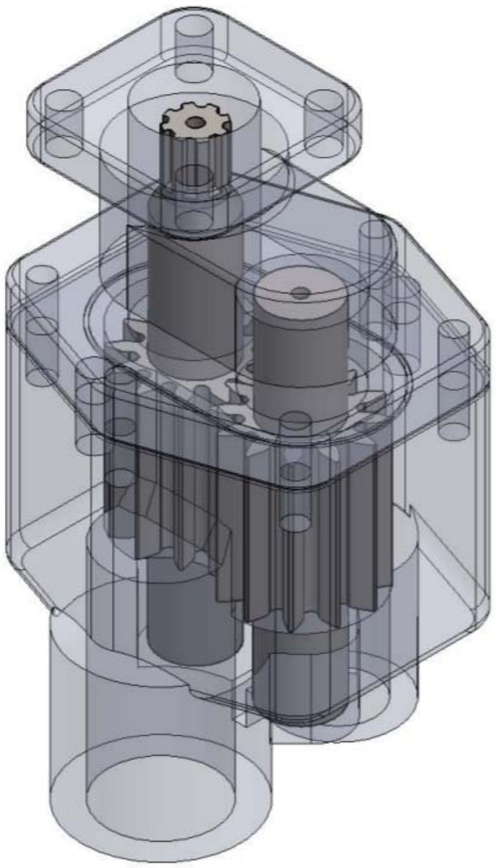

Figure 1.0.1 POWAUTO Gear Pump Model

Advantages of gear pumps are that high speed and high pressure can be achieved, and there is a large degree of flow control because of the simple displacement mechanism and tight clearances. Disadvantages of gear pumps are that any solids in the fluid can cause failure due to the tight clearances and the bearings in the liquid area, and that manufacture is expensive due to the accuracy required.

It functions by using a motor to turn the drive gear in the direction of the desired flow of hydraulic fluid, which turns the driven gear. The hydraulic fluid is captured by the teeth of the gears, and is transported through the pump, away from the inlet port and out the outlet port. This is shown in Figure 1.0.2.

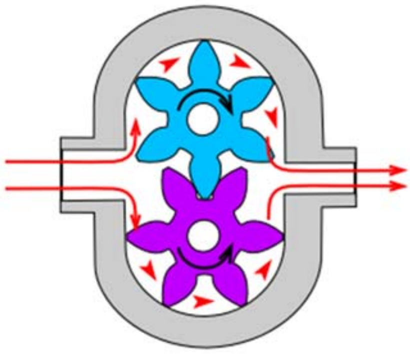

Figure 1.0.2 Gear pump flow (Source: Wikimedia Commons 2005)

The inlet port is made larger than the outlet port to avoid cavitation (bubbles forming). If bubbles form, they collapse when they pass into the higher pressure region of the outlet port. This causes vibration and noise, and damages the components of the pump (Parkhurst 2014). When the inlet port is larger, water can flow in freely and cavitation will not occur.

1.1 Analysis of components

1.1.1 Head

The top part of the casing of the pump is the head. The critical dimensions of the head are the positioning and diameters of the holes for the dowels on the underside of the head, and the bores for the bearings. The positioning of the dowel holes is critical as the dowels align the head with the body of the casing. If the head and casing aren't aligned, the gears won't fit, and the pump won't be able to be assembled or operate. The diameters of the dowel holes are critical as one dowel is press fit and one is free to move, and so must be machined to tolerances of +/- 0.015mm to ensure that they perform these functions.

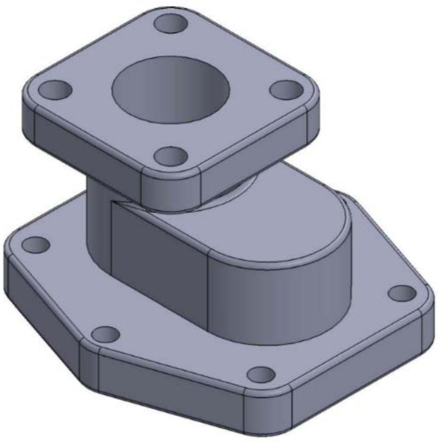

Figure 1.1.1 Pump head

1.1.2 Body

The body of the casing is where the gears operate, and where the inlet and outlet ports are. The critical dimensions on the body are the diameter of the bores in which the gears turn, the bores for the bearings, and the positioning and diameters of the holes for the dowels. The diameter of the bores in which the gears turn is critical because in order to maintain pressure, the space between the gears and casing should be small enough to stop fluid from flowing through, approximately []mm at a pressure of 28MPa. The diameter of the bores also needs to be large enough that the gears can turn with minimal friction, reducing the power required to operate the pump and increasing the maximum flow rate.

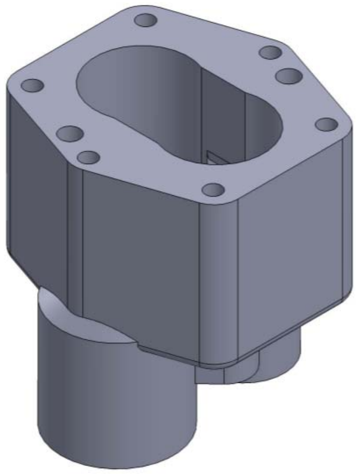

Figure 1.1.2 Pump body

1.1.3 Bushings

The pump uses fluid film bearings, with the hydraulic fluid functioning as the lubricant. There are 4 bushings in the pump, two in the head and two in the body. The inside diameter of the bushings is critical as the gear shaft needs to rotate inside the bearing with minimal friction, but also without rocking side to side and causing unnecessary wear and noise during operation. The tolerance for the inside diameter is +/- 0.005mm. The outside diameter of the bushings is also critical, as the bushings must be press fit into the head and body of the pump. The tolerance for the outside diameter is +/- 0.015mm.

1.1.4 Dowels

The dowels are used to align the two pump housing segments. One dowel is press fit and so has a diameter equal to the diameter of its hole (Brown 2017), and one dowel freely slides in and out and so has a slightly smaller diameter than the diameter of its hole. Both diameters of the dowels are machined to tolerances of +/- 0.015mm so that they can perform these functions.

1.1.5 Gears and gear shafts

The gears and gear shafts are a single part. The gears function to transport the fluid under pressure from the inlet port to the outlet port. Both the diameter and length of the gears are critical in order to maintain pressure, and only allow fluid to flow between the teeth of the gears and not around the edge of the gears. As with the bores in the casing, having accurate dimensions optimises both the pressure and the flow rate.

The diameters of the gear shafts are critical as they turn inside the bearings, and so have the same accuracy requirements as the bearings. The diameter of the gear shaft must be smaller than the diameter of the bearing by at least the combined surface roughness of the gear shaft and bearing, and so is determined by the machining processes used to produce both components.

1.1.6 Seals

The shaft seal is an elastomer ring bonded to a metallic ring in the head of the pump, around the shaft of the driver gear. It separates the internal chamber of the pump from the air, and is critical in maintaining pressure internally. As there is relative motion between the shaft of the driver gear and the head of the pump, there is a distance of approximately 0.0025mm between the seal and gear shaft, so that the hydraulic fluid can lubricate the driver shaft and reduce friction between the shaft and seal. This also reduces heat degradation of the seal and prolongs its life.

The case seal is an elastomer ring that seals the head and body together. The bottom surface of the head and top surface of the body are milled flat to a high accuracy so they can create a seal, and the case seal functions as a backup to ensure the seal remains intact.

1.1.7 Wear plates

The wear plates are positioned at either end of the gears. Their purpose is to prevent wear on the gears and pump body by wearing first. They are therefore made of a soft metal and designed to be relatively cheap and easily replaceable.

1.2 Diagram

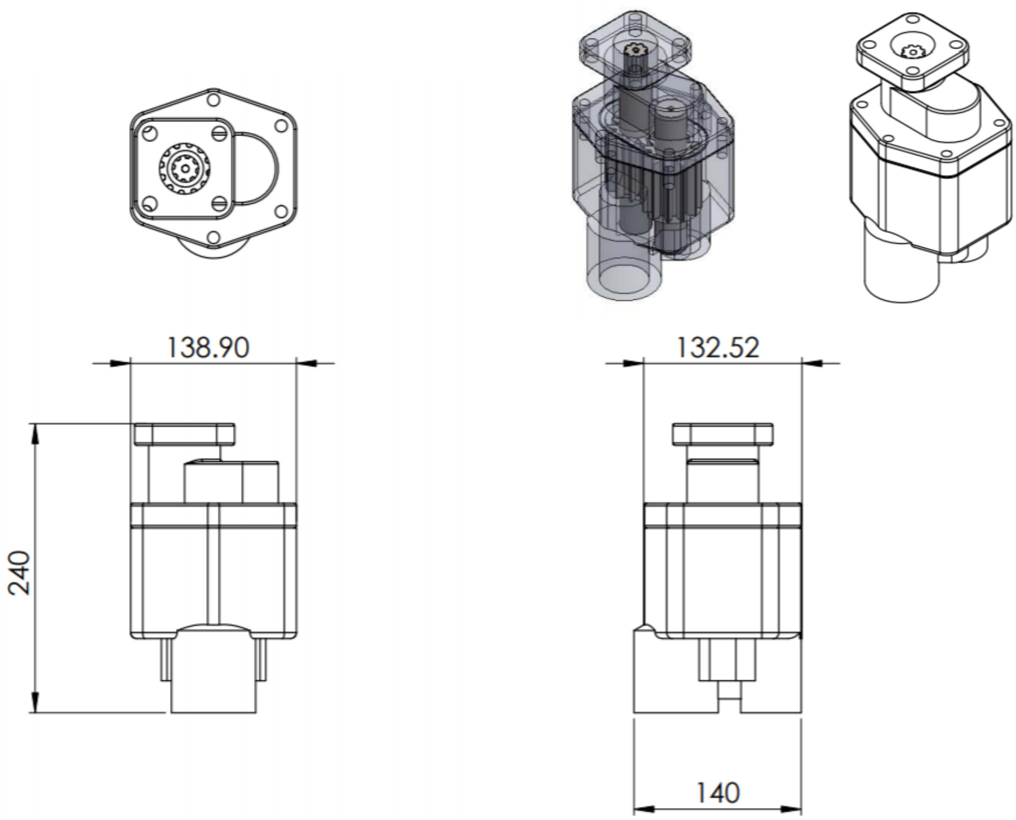

Figure 1.2.1 Diagram of POWAUTO Gear Pump

Table 1.2.1 POWAUTO Gear Pump parts list

Part No.	Description
1	Shaft seal
2	Bolt
3	Head
4	Bushings
5	Case seal
6	Axial seal
7	Wear plate
8	Driver gear
9	Driven gear
10	Dowel
11	Body

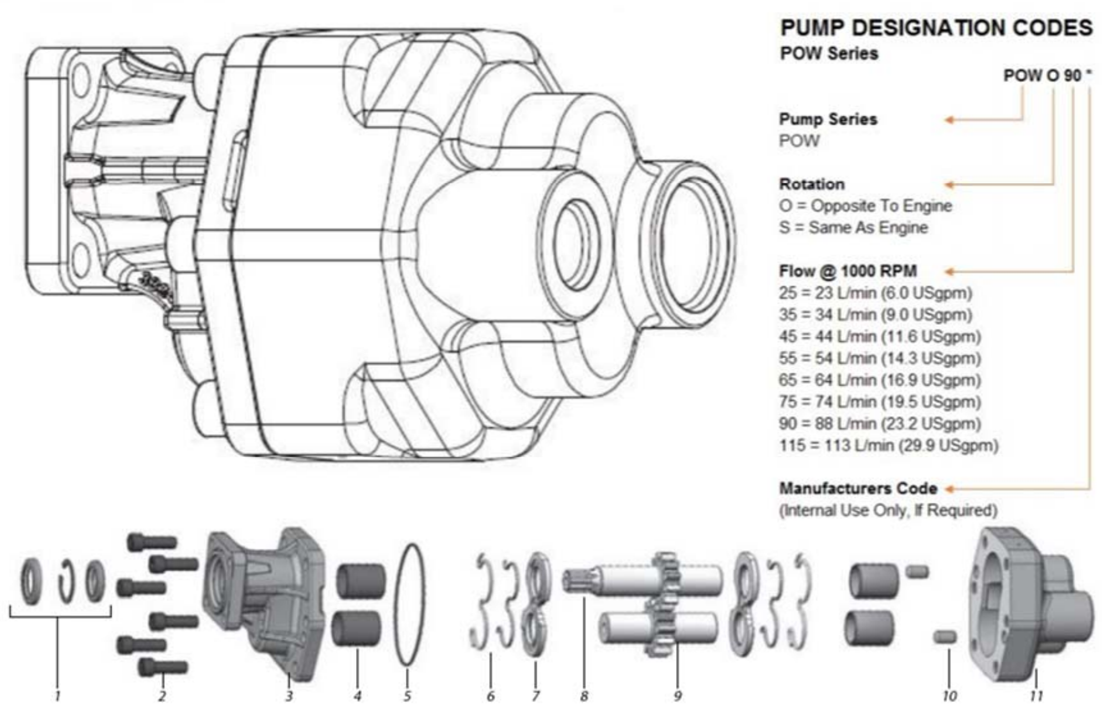

Figure 1.2.2 Exploded view diagram of POWAUTO Gear Pump (Source: Hydreco 2017)

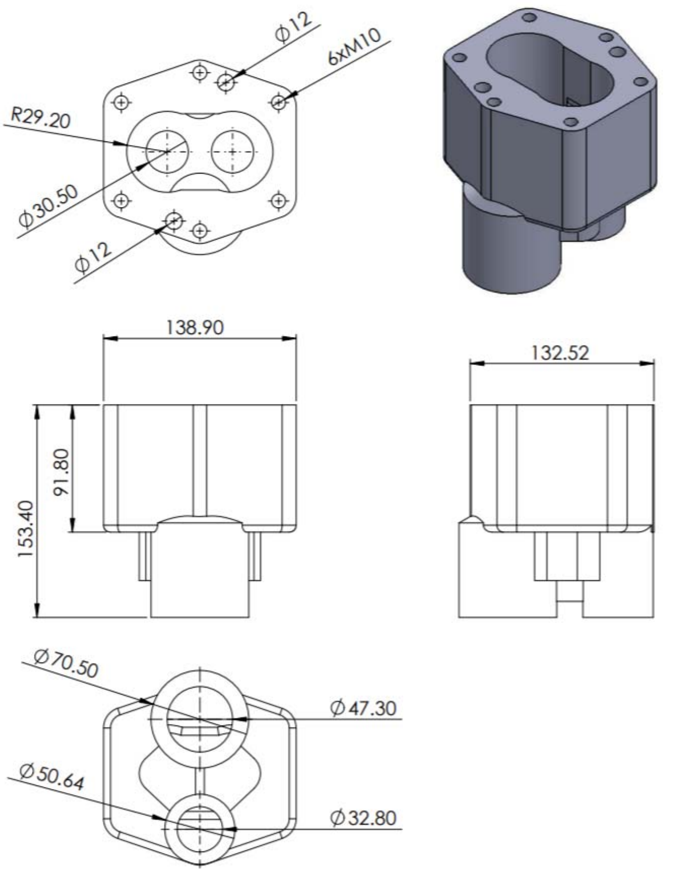

Figure 1.2.3 Diagram of pump body

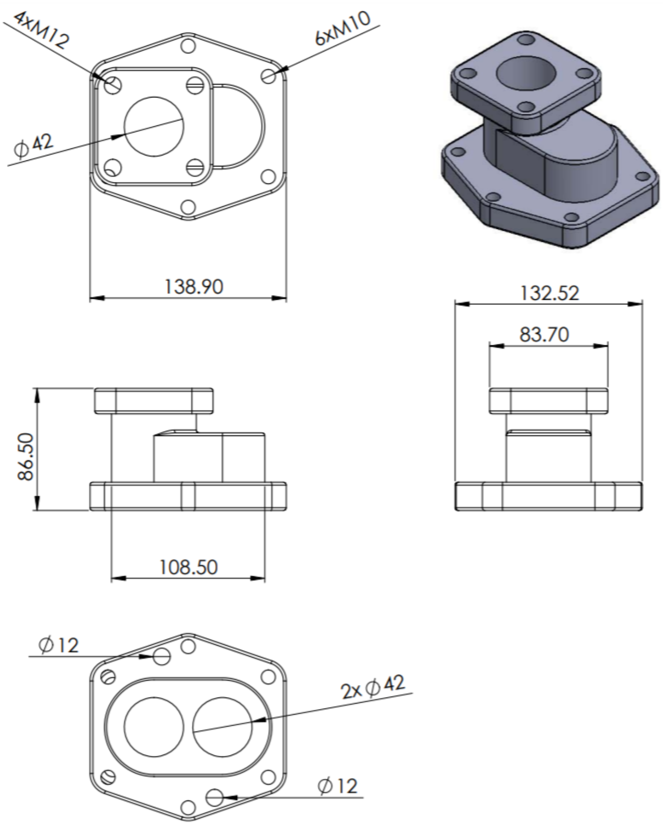

Figure 1.2.4 Diagram of pump head

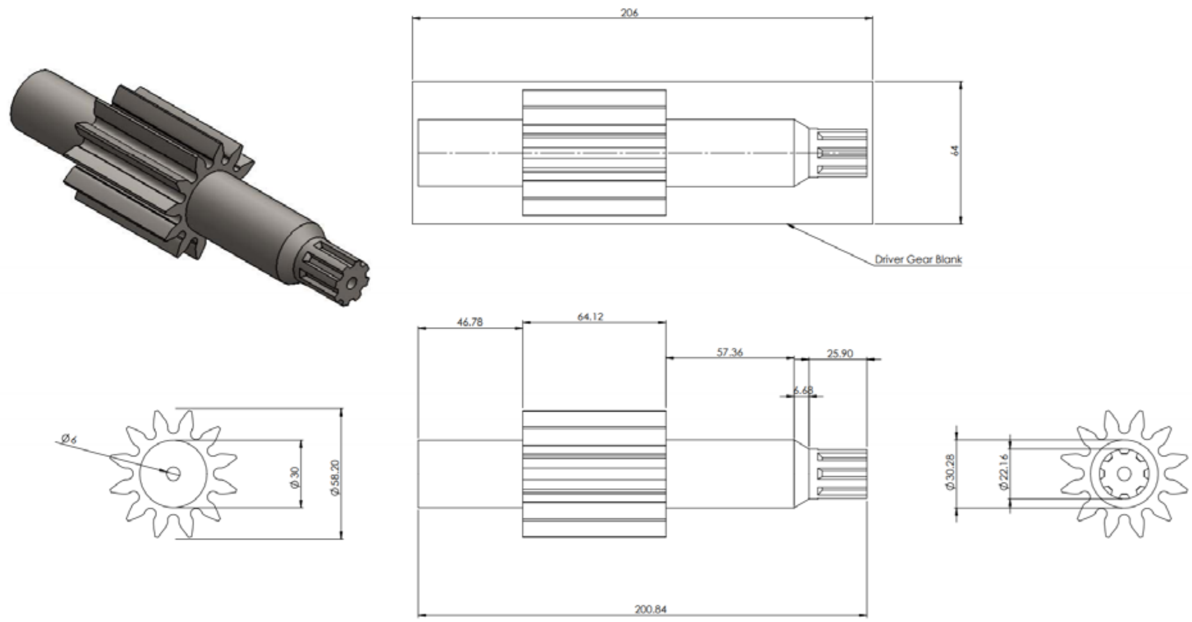

Figure 1.2.5 Diagram of driver gear

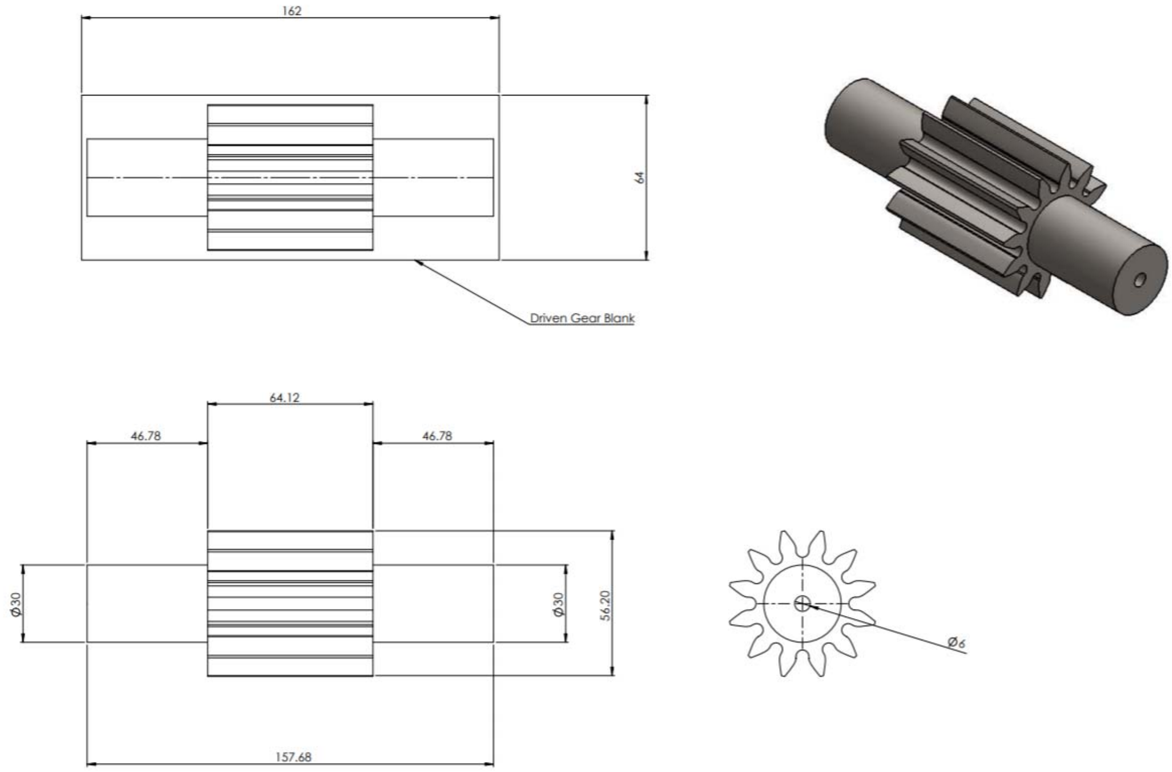

Figure 1.2.6 Diagram of driven gear

2.0 Materials

2.1 Casing (head and body)

The main property desired for the casing is good machinability, as a number of operations need to be performed to achieve the interior tolerances required. High strength is also required, as the casing needs to withstand the pressures exerted by the fluid inside.

ISO 400-18 spheroidal graphite cast iron (SG iron) is used for the casing. It has good machinability of 70-76%, compared to 100% machinability for AISI 1212 steel. It also has a relatively high yield tensile strength of 310MPa, and a high modulus of elasticity, and so is suitable for this high pressure application.

As cast iron is not corrosion resistant, once the pump is assembled it is given a protective outside coating to prevent corrosion. The inside does not need a protective coating, as no water will be in contact with it, only oil based hydraulic fluid.

2.2 Bushings

The bushings are made of steel, and coated with PTFE (Teflon). During start-up of the pump, hydraulic fluid may have drained from the bearings, leaving no lubrication. PTFE has a very low coefficient of friction of 0.05–0.10, and so the coating reduces friction between the bushings and shaft, reducing wear during start up (AFT 2018).

2.3 Dowels

The dowels are made of SG iron like the casing. The same material is used so that the thermal expansion of the dowels and casing are the same, and so the fit is the same at operating temperatures as it is at room temperature.

2.4 Gears/gear shafts

The properties required for the gear/gear shaft part are very high strength, elasticity, and hardness. High strength and elasticity are required due to the high pressures that are exerted on the gears during operation by the hydraulic fluid. High hardness is required to improve the wear resistance of the gears as the gears have many critical dimensions, and once they wear past the tolerance specified they must be replaced.

The material used for the gears is AISI 4340H steel bar stock. The high yield tensile strength of 475MPa resists bending under the force exerted, and the high modulus of elasticity of 192GPa means that it would bend rather than shattering if there was a malfunction and the pressure grew too high, reducing possible damage to other components.

2.5 Seals

The shaft seal is a ring made from SG iron, with a rubber ring bonded to the inside of the iron ring. The case seal is made of rubber.

2.6 Wear plates

The material properties required in the wear plates are low hardness, and ease of machineability. Aluminium is chosen for the wear plates as it is soft, with a Brinell hardness of 95, compared to the hardness of the gears at 217 and the hardness of the casing at 160. Its ease of machinability brings down the cost and time to manufacture, making it relatively cheap to replace.

Table 2.0.1 Material properties (Data source: Matweb 2000, Matweb 2001)

	AISI 4340H Steel (annealed at 810 C)	ISO 400-18 SG Iron 60-40-18	ISO AlMg1SiCu
Brinell hardness	217	160	95
Yield tensile strength	475 MPa	310MPa	276MPa
Elongation at break	22%	18%	12%
Modulus of elasticity	192 GPa	180GPa	68.9GPa
Machinability (based on 100% machinability for AISI 1212 steel)	50%	70-76%	300-400%
Thermal conductivity	44.5 W/mK	36 W/mK	167 W/mK
Melting point	1427 C		
Density	7850 kg/m^3	7200 kg/m^3	2700 kg/m^3

3.0 Manufacturing

3.1 Casing

The casing of the hydraulic gear pump is sand cast from SG iron. The inner chamber, holes for bearings, bolt holes, and dowel holes are then bored. The top face of the body and bottom face of the head are faced off so that they fit together. The bolt holes are tapped. Once the pump is fully assembled, a protective coat of paint is sprayed on to prevent corrosion.

1. An aluminium cope and drag pattern is used for both the head and body. A core box is used to make the core for the inner chamber and inlet/outlet ports. Aluminium is used for the pattern as it is durable, and is easy to machine.
2. A green sand mold is used, with a makeup of 82% silica, 10% bentonite clay, 4% carbon, and 4% water. The surface roughness after casting can be high as later machining is necessary regardless, so silica sand is used as it is cheap. Due to the high production rate, a continuous sand mixer is used to mix all components of the sand together, along with recycled sand from previous castings.
3. The cope and drag sections of the pattern are placed in flasks. Sand is pressed around them, and is vibrated to remove air. Sand is also pressed into the core box, and is vibrated to remove air.
4. The formed mold halves and core are positioned together, and clamped. A water based release agent is used to lubricate the inside of the mold, so that the casting can be easily removed. The mold halves are checked for alignment before pouring to avoid mold shift.
5. The iron is melted in a pouring furnace, and the molten SG iron is poured slowly at a temperature of 880C into the mold. A pouring furnace is used for this because of the high production rate, the fixed cost of the pouring furnace is significantly cheaper than the ongoing cost of labour if a person were employed for this procedure. A machine also has greater control over the rate of flow and temperature of metal than a human, which minimises possible defects in the part.
6. The cast is cooled in a furnace at 55C, until the cast reaches a temperature of 345C. It is then air cooled. This is the recommended practice to achieve Grade 60-40-18 ductile iron (Ductile Iron Society 1998).
7. Once the temperature of the cast reaches 65C after approximately 12 hours (Mullins 2006), it is removed from the sand mold by vibrating the mold to break up the sand. It is then tipped upside down to ensure all the sand is removed.
8. The top face of the body and bottom face of the head are milled down, so that the surface roughness does not exceed 0.01mm. This is done by rough cutting 1mm off the surface of each face, then performing a finishing cut removing 0.2mm.
9. A CNC drilling machine is used to dimension the inner chamber to the required accuracy. The space that the gears turn in is drilled to a diameter of 58.4mm in the body, and the holes for the bushings are drilled in both the head and body.
10. A multiple spindle drill with HSS tooling is used to drill the 6 10mm bolt holes in both the head and body. The casing is then moved to another multiple spindle drill, which is used with a tap to thread the holes with an M10 thread. Multiple spindle drills are used for this process as there is as high production rate, so reducing the production time as much as possible is desired. If a CNC drilling machine were used, it would take over 6x longer to perform this step as each hole would be drilled individually and it would take time for the drill to move to each hole.
11. The seal groove in the head is cut in a CNC mill.
12. The dowel holes are cut using a drill with a 12mm HSS drill bit. This has a precision of approximately 0.01mm (Endo et al. 2007). An accuracy of +/-0.015mm is required, so this equipment is acceptable for this application. If a higher accuracy were required, the

material of the cutting edge of the drill could be changed to tungsten carbide or cobalt HSS, or helical interpolation could be used with a smaller tool.

3.2 Bushings

The bushings are made from steel tube stock, with an outer diameter of 42mm and an inner diameter of 30mm. The tube stock is rough cut to a length of 35mm. Outer diameter grinding and bore grinding is done to machine the outer and inner diameters to the required tolerances. Face grinding is then done to finish the edges of the bush. The inside of the bush is then spray coated with PTFE to give a low friction coating.

3.3 Dowels

The dowels are machined from iron bar stock. They are rough cut to a length of 30mm. The diameter of the press fit dowel is machined on a lathe to 12mm +/-0.015mm, and the diameter of the slide fit dowel is machined on a lathe to 11.9mm.

3.4 Gears

The gears are machined from 64mm diameter AISI 4340H steel bar stock. The gears could have been cast and then machined to the correct dimensions to reduce material wastage. However, this would extend the manufacture time, and increase the equipment cost as additional equipment would be required for casting. The material wastage caused by machining the gears is 71.5%, given a blank volume of 662700mm^3 and a finished volume of 188560mm^3.

1. Bar stock is transported to the lathe on rollers, which distribute the weight of the bar evenly across its length and ensure it is not bent.
2. The bar stock is cut to lengths of 206mm in a CNC cut off saw. This is 5mm greater than the final length, and so allows material for milling each end to finish to the correct tolerances.
3. The base of the driver gear is clamped in the chuck of the lathe, and multiple rough cuts are performed using an HSS rough cut tool to shape the gear. 1-2 finishing cuts are performed on the surfaces of the gear. These cuts are detailed in Table 3.4.1.

Table 3.4.1

Area of cut	Cut no. (in order of operation)	Type of cut	Depth of cut (mm)	Length of cut (mm)	Speed (RPM)	Time (s)	Diameter after cut (mm)
Whole	1	Rough	2.5	156	330.5	28.3	59
Shaft	2	Rough	2.5	92	361.1	15.2	54
Shaft	3	Rough	2.5	92	398.0	13.9	49
Shaft	4	Rough	2.5	92	443.2	12.5	44
Shaft	5	Rough	2.5	92	500.0	11.0	39
Shaft	6	Rough	2	92	557.1	9.9	35
Shaft	7	Rough	2	92	629.0	8.8	31
Spline	8	Rough	2	26	722.0	2.2	27
Spline	9	Rough	2	26	848.0	1.8	23
Gear	10	Finish	0.2	65	332.8	58.6	58.6
Gear	11	Finish	0.2	65	335.1	58.2	58.2
Shaft	12	Finish	0.3	58	641.4	27.1	30.4
Shaft	13	Finish	0.2	58	650.0	26.8	30

Spline	14	Finish	0.2	26	862.8	9.0	22.6
Spline	15	Finish	0.2	26	878.4	8.9	22.2

4. The top of the driver gear is then clamped in the chuck, and a similar process is performed for the lower shaft of the gear, taking off material in rough cuts and then performing 2 finishing cuts. This is detailed in Table 3.4.2. The driver gear at this step is shown in Figure 3.4.1.

Table 3.4.2

Area of cut	Cut no. (in order of operation)	Type of cut	Depth of cut (mm)	Length of cut (mm)	Speed (RPM)	Time (s)	Diameter after cut (mm)
Shaft	16	Rough	2.5	50	330.5	9.1	59
Shaft	17	Rough	2.5	50	361.1	8.3	54
Shaft	18	Rough	2.5	50	398.0	7.5	49
Shaft	19	Rough	2.5	50	443.2	6.8	44
Shaft	20	Rough	2.5	50	500.0	6.0	39
Shaft	21	Rough	2	50	557.1	5.4	35
Shaft	22	Rough	2	50	629.0	4.8	31
Shaft	23	Finish	0.3	50	641.4	23.4	30.4
Shaft	24	Finish	0.2	50	650.0	23.1	30

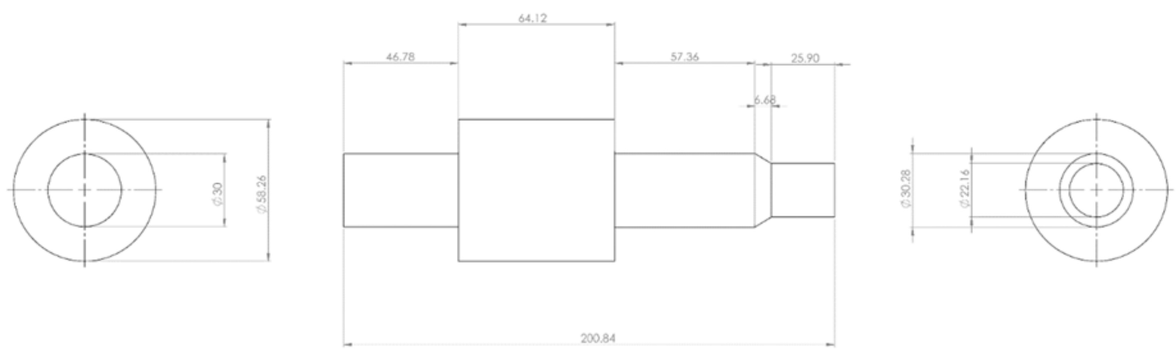

Figure 3.4.1 Driver gear after turning

5. As the gears are large, linear broaching is used to cut the 12 gear teeth on both the driver and driven gear. A CNC broaching machine with HSS tooling is used to accomplish this process. Broaching with a CNC broaching machine is also used to cut the spline on the drive shaft.
6. Face milling is done at each end of the gear to bring the total length of the drive gear to 201mm +/- 0.4mm, and to bring the length of the driven gear to 158mm +/- 0.4mm. 2mm are taken off each end in a rough cut, and
7. A 6mm hole in the centre of the gear is drilled.

8. The gears are heat treated to remove residual stresses from machining, and to increase hardness, wearability and therefore the life of the gear. To do this, they are heated in a furnace to 810 C, then allowed to cool by air.

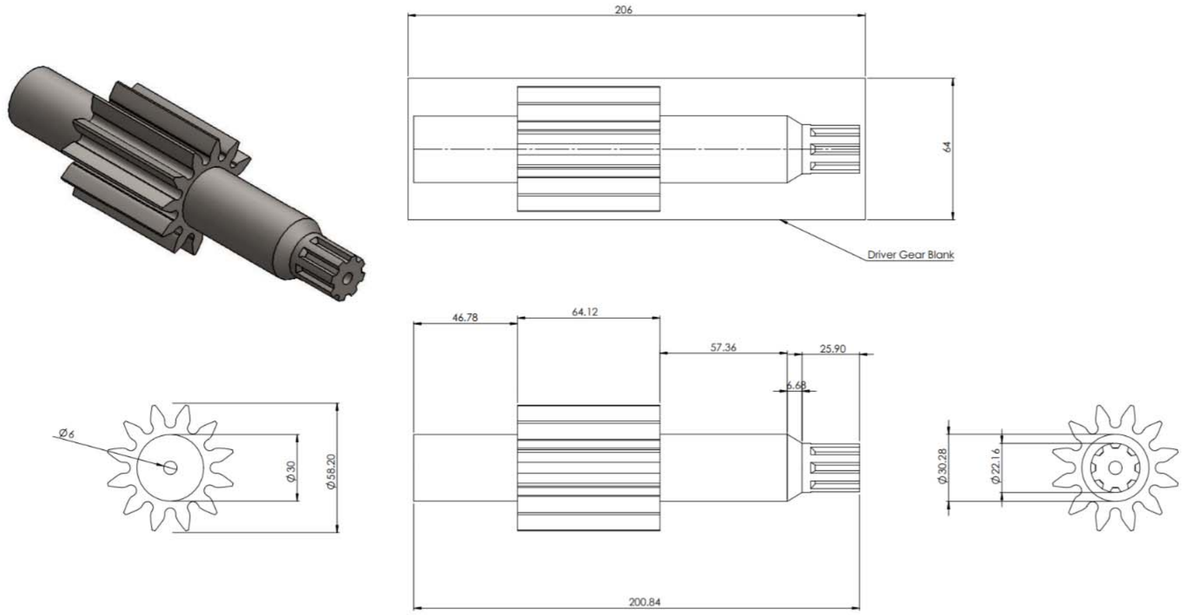

Figure 3.4.2 Driver gear and blank

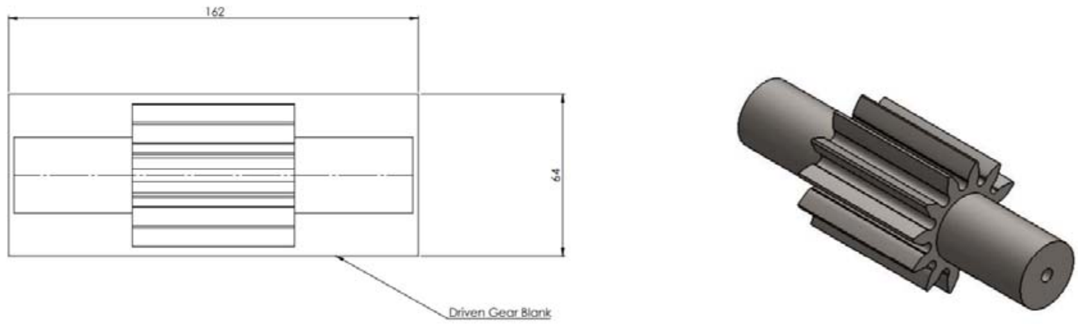

Figure 3.4.3 Driven gear blank

3.5 Seals

The rubber parts of both seals are injection moulded. Injection moulding is done as a high precision can be achieved, there is no flash to be removed, it is a fast process and economical for high production rates, and it is a near net shape process.

The metal part of the drive shaft seal is machined from steel tube stock. The rubber part of the drive shaft seal is then fused to this metal ring.

3.6 Wear plates

The wear plates are die cast aluminium. Dies are initially expensive, but as the wear plates are expected to be replaced several times throughout the life of the pump the production quantity of wear plates is high, so a high initial equipment cost can be justified. The material of the die is hardened tool steel because it has high hardness, thermal shock resistance, machinability, and is relatively cheap. Due to the melting point of aluminium being fairly high, casting is done in a cold chamber die casting machine, as the plunger in a hot chamber machine can be damaged by high heat. The aluminium is melted in a furnace, and is poured into the shot chamber of the die casting machine. It is then pushed into the cavity of the die with a piston. Once the aluminium has been cast and cooled, it is removed from the die and the flash and sprue are trimmed using a grinding wheel.

3.7 Assembly

In assembly, the bushings are press fit into the head and body of the pump. The shaft seal is press fit into the head, and the case seal is placed in the seal groove. The dowels are fit into the body of the pump, and the gears are placed inside. The head is then pushed onto the body of the pump, the dowels lining it up correctly. The assembled casing is then sprayed with oil based enamel paint, providing a protective layer against corrosion. Enamel paint is used as it is durable and commonly used for outdoor applications.

4.0 Quality Assurance and Inspection

At the completion of manufacture of each part, the part is weighed, and critical dimensions measured with a 3D laser scanner with a precision of 5um. The casing and gears of the pumps are inspected for cracks using magnetic particle inspection.

One head, one body, and one gear are randomly selected each day for manual inspection. They are visually inspected, strength tested, and hardness tested. They are measured for distance, surface roughness, and linearity using a high performance laser distance sensor with a precision of 0.7um.

5.0 Estimation of Manufacturing Cost

Table 5.0.1 gives an estimation of the total time to manufacture. Some of these processes can be performed concurrently, and so the time to manufacture could be significantly reduced.

Table 5.0.1 Manufacture time estimate

Component	**Time estimate**
Casing	14 h (including cooling)
Bearings	30 min
Dowels	10 min
Gears	1 h
Seals	30 min
Assembly	10 min
Total:	**16 h 20 min**

There is minimal labour required in the manufacturing process, as the majority of steps are automated. Labour is required to calibrate the machines, move raw materials to machines, perform quality control on randomly selected parts and assembled pumps, and supervise processes to ensure that nothing has gone wrong.

Table 5.0.2 gives approximate costs for the equipment used during manufacture.

Table 5.0.2 Manufacture equipment cost estimate

Equipment	**Approximate cost (AUD)**
CNC drill	75000
CNC mill	75000
Broaching machine	12000
Green sand mixer	5000
Mold compacter	5000
Pouring furnace	15000
Mold remover	10000
Die casting equipment	30000
Rubber injection moulding equipment	10000
Paint sprayer	1000
PTFE sprayer	1000
Total:	**239000**

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