

Chapter 5 – Machine Manufacturing

This chapter contains information regarding the manufacturing of the LS PMSM prototype. It includes the techniques used as well as design deviations made to the design to make assembly possible. The goal of the chapter is to provide insight into the construction of the machine using pictures, photos and drawings. This chapter is divided into stator manufacturing, rotor manufacturing and final assembly. Unsuccessful methods are also discussed to aid future machine design.

5.1 Manufacturing process

As indicated in Figure 5.1, the manufacturing of the machine is divided into 3 sections. Each of these contains various sub-stages that are discussed in depth under the corresponding subsections. The manufacturing process is also shown in Figure 5.1

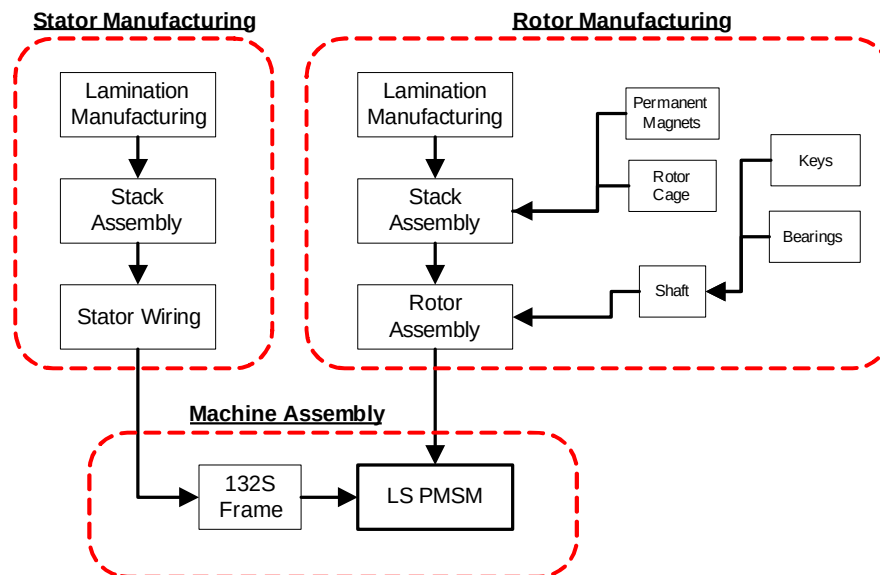


Figure 5.1: LS PMSM manufacturing and assembly diagram

The main machine manufacturing sections is indicated by the red dashed block and the sub stages by the black blocks. A detailed manufacturing plan is supplied for each sub-stage as well as the manufacturer, cost and manufacturing time.

5.2 Stator manufacturing

As indicated by Figure 5.1 the stator consists of three manufacturing stages. Since the laminations and stack assembly was done by the same company. The discussion of these two sub components is combined in this section.

5.2.1 Lamination and stack manufacturing

As the machine is a once off order possible manufacturers were limited. As a result Actom's Laminations & Tooling division situated in Benoni was used. Table 5.1 contains the manufacturing information as used by Actom.

Table 5.1: Stator stack manufacturing information

	Yoke
Lamination material	M400-50A
Lamination manufacturing technique	Laser cut
Stack assembly method	Welding on the D_{so}

The manufacturing techniques used to produce the stator stack laminations for small machines differ from that of a mass produced stator stack. If large quantities of laminations are required over a long period of time they are usually punched instead of laser or wire cut. Once-off orders can also be punched, but the cost of the punching die is usually higher than the entire cost when laser or wire cut is used. Punch lamination can be used if a pre-existing lamination design is used. Lamination manufacturing technique also introduces additional losses in the machine that is unique to the technique. According to [25], laser cutting is most commonly used of prototype and special machines but adds the highest value of additional losses; these losses are very low in small low frequency machines and don't have significant influence on the efficiency. A graphical representation of an actual study done on various cutting techniques is provided in [27]. It clearly indicates that laser cutting the laminations has the biggest influence on the BH properties of the material. This is accredited to the high temperature introduced by the laser on the lamination edges

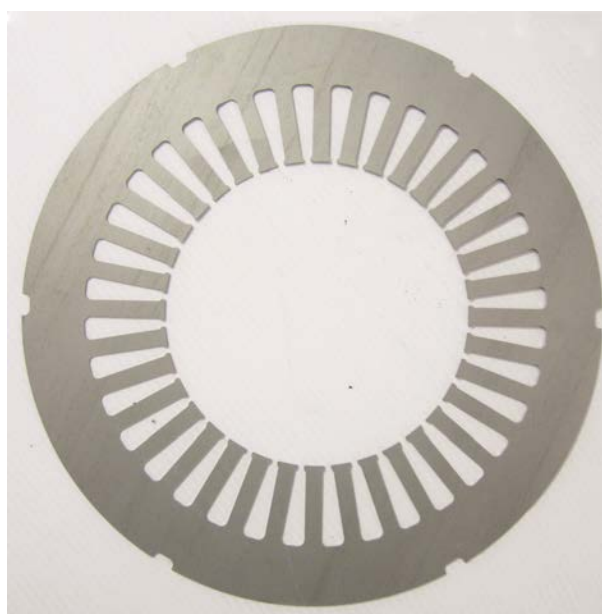


Figure 5.2: Photo of a single stator lamination manufactured by Actom

To assemble the stator stack, 6 cleating notches are placed on the outside diameter of the laminations. This is seen in Figure 5.2. Except for the cleating notches all the dimensions are as mentioned in Chapter 5. According to Actom, the laminations are within 0.1mm of the supplied dimensions. All the laminations used in the stator stack were individually inspected and any defected laminations were replaced before the stack was assembled. Figure 5.3 is a closer image of the lamination for a better representation of the slot shape. In the figure two laminations are placed one on top of the other.

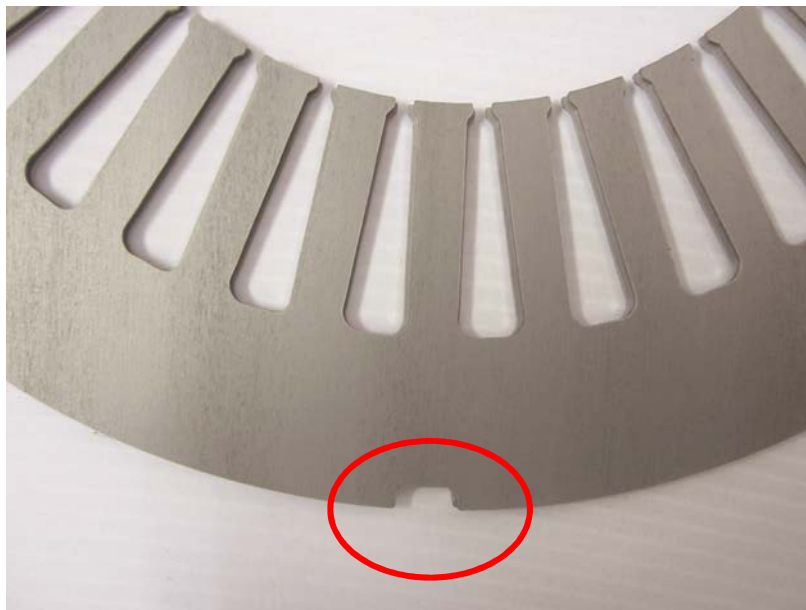


Figure 5.3: Photo of the actual stator slot

When a stator is not skewed, steel cleating strips are placed in the notches to hold the laminations in place, but this method could not be used since skewing is incorporated in the stator design. Thus the stator laminations were welded together on the notched, as this would not increase the outside diameter of the stack. The disadvantage of welding the stator is the increase of iron losses as the laminations are electrically connected by the welds and the heat due to the welding changes the permeability of the electric steel. The loss impact due to welding is however very low in small machines, between 0.5 – 1% per welding point [25 - 27]. Figure 5.4 shows two of the welds used to construct the stator stack.

Figure 5.5 and 5.6 contains images of the completed stator stack. In addition to the M400-50A laminations, a 1.6mm thick mild steel plate was placed on both ends of the stack. This is to eliminate lamination flaring that occurs at the slot teeth. From the [25 – 27] the conclusion is made to manufacture the most efficient stator stack, ideally a stator must be manufactured by punching the laminations instead of laser cutting them. To assemble the stack, the laminations must be pressed against each other using a hydraulic press and inserting cleating strips in the notches. Care must be taken not to apply too high a force on the stack as this can also introduce added losses in the core.

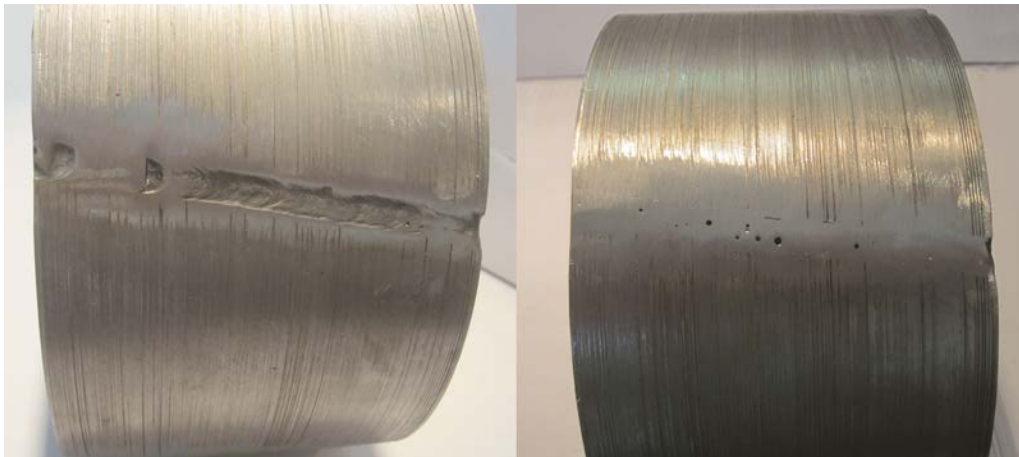


Figure 5.4: Stator stack welds



Figure 5.5: Photo of stator stack

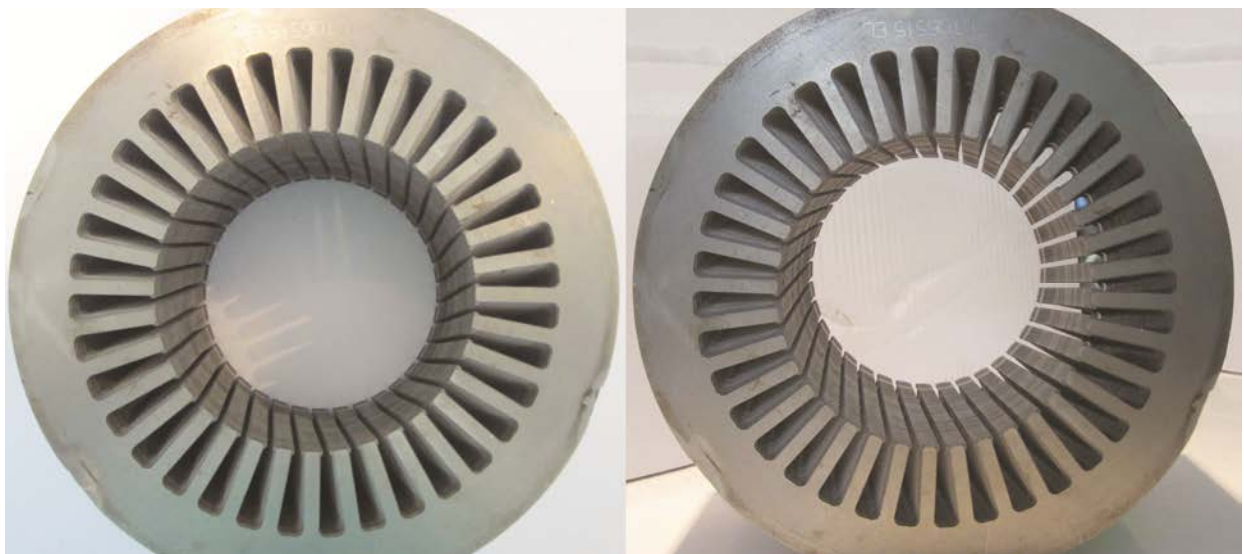


Figure 5.6: Front views of stator stack

5.2.2 Stator coil winding

The winding configuration of the stator is listed in Table 5.2 and Table 5.3. Both tables only represent half the stator slots but this is all that is needed due to symmetry. Table 5.2 contains the phase distribution of the three phases and Table 5.3 contains the coil representation in a given slot. The negative sign represents the direction of the current flow in the slot.

Table 5.2: Phase distribution of stator windings

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19/1
Bottom	-b	a	a	a	-c	-c	-c	b	b	b	-a	-a	-a	c	c	c	-b	-b	-b
Top	a	a	a	-c	-c	-c	b	b	b	-a	-a	-a	c	c	c	-b	-b	-b	a

Table 5.3: Phase coil representation in stator slots

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19/1
A	0.5	1	1	0.5						-0.5	-1	-1	-0.5						0.5
B	-0.5						0.5	1	1	0.5						-0.5	-1	-1	-0.5
C				-0.5	-1	-1	-0.5						0.5	1	1	0.5			

From Table 5.3 it is clear that in some slots half a coil is required. This means is that if a single layer stator is used and the number of turns per phase in a slot is equal to 10, only 5 turns will be used in this double layer configuration. The slot still contains 10 turns but it may be from two different phases as in slot 1 in Table 5.3. The total number of turns, N_s , will still be the same.

The winding of the stator was outsourced to Marthinusen & Coutts situated in Cleveland east of Johannesburg. The company wound, vacuum pressure impregnated (VPI) and fitted the stator in the cast-iron frame.

There was a misunderstanding regarding the winding layout that only came to light on completion of the manufacturing. The correct manufacturing orders were followed; however there was a communication mistake regarding the amount of turns per slot. The end product still had the correct layout as in Table 5.2 and 5.3 but the amount of turns was nearly double. The turns per coil slot were reduced from 36 to 32 as the fill factor of the slot was too high (over 50 %). The double wire per turn was replaced by a single wire as the increase in wires per slot and the high packing factor made it virtually impossible to use two wires per turn. Table 5.4 contains the difference between the designed stator and the final manufactured stator.

Table 5.4: Difference in stator winding arrangement from design and manufactured

Component	Design	Manufactured
N_s	216	384
Turns per slot	36	$2 \times 32 = 64$
Wire per turn	2	1
Copper wire diameter	$2 \times 1 \text{ mm}$	$1 \times 1.32 \text{ mm}$

Two options were available regarding the stator. The first option was to rewind the stator according to the design. However this would lead to a time delay which at that time could not be afforded. Thus the second option was investigated. As the motor is designed to be used in star configuration the second option is to determine if the stator can be used in delta configuration. By connecting the stator in star the stator resistance is nearly double the calculated value. There are several other complications as well with regards to back-emf, torque production etc. due to the properties linked to delta connection. The majority of these problems can be overcome and the stator resistance and inductance is similar to that of a star connected machine. Simulations in ANSYS Maxwell[®] confirmed that connection in delta will be a feasible solution.

Figure 5.7 and Figure 5.8 are photos of the stator already pressed into the frame and before and after the VPI process.

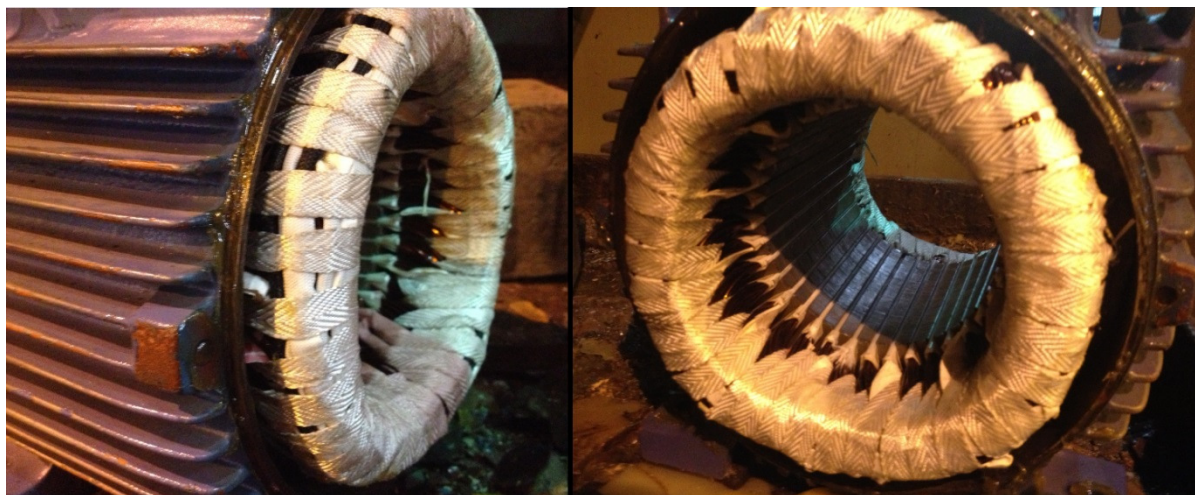


Figure 5.7: Winded stator stack before VPI

After the VPI process the stator teeth air gap area was polished to remove the remaining resin of the VPI processes. Although the end windings are outside the centre frame section the end caps still fit on the centre frame and there is adequate clearance between the end windings and end caps.



Figure 5.8: Winded stator stack after VPI

5.3 Rotor manufacturing

The rotor assembly for the prototype is much more complex and consists of more components than the stator, see Figure 5.1 for details. The rotor components had to be designed specifically for the prototype before it could be manufactured. Figure 5.9 shows the rotor manufacturing process in more detail.

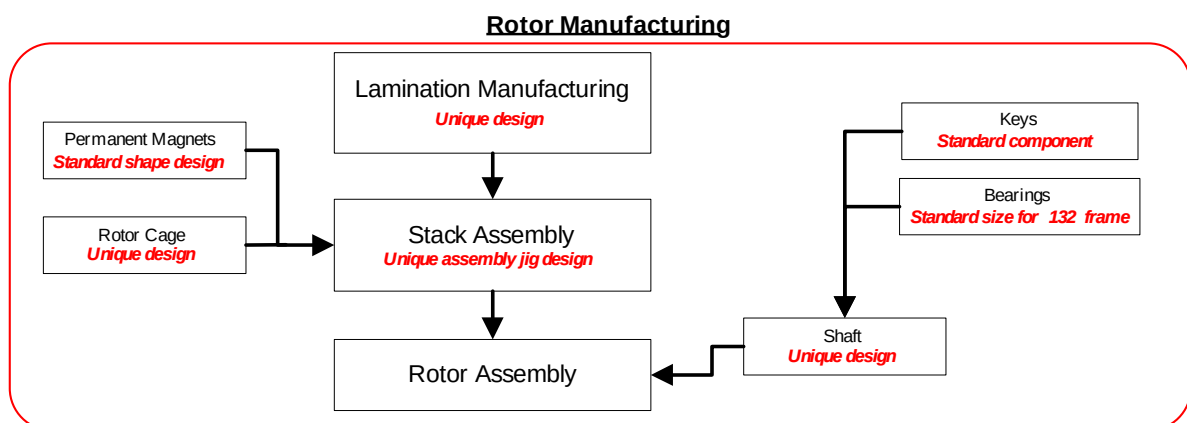


Figure 5.9: Rotor assembly diagram

The manufacturing list for each component is indicated in Table 5.5. It contains either the supplier or the manufacturer of the component. The majority of the components were manufactured in South Africa except for the PMs that were manufactured by Bakker Magnetic located in Eindhoven, The Netherlands. NWU Instrumentmaking is located on the North-West University campus.

Table 5.5: Component manufacturing & supplies list

Component	Supplier/Manufacturer
Laminations	Actom: Laminations and tooling
PMs	<i>Bakker Magnetics</i>
Rotor Cage	NWU Instrumentmaking
Bearings & Keys	<i>Bearing man</i>
Shaft	NWU Instrumentmaking
Assembly Jig	NWU Instrumentmaking
Rotor Assembly	NWU Instrumentmaking

Each of the rotor components is discussed under its own sub-section. The rotor shaft, keys and bearing assembly are combined under one sub-section as this forms part of the completed shaft.

5.3.1 Laminations

The rotor laminations were also manufactured from M400-50A electrical steel. The same manufacturer and techniques were used for the rotor laminations and the stator laminations. The dimensions of the laminations differ from that as selected in Chapter 3. To establish a sliding fit for the PMs in the rotor, the magnet slots size was increased by 0.1 mm for both the length and width. Figure 5.10 is a photo of the rotor lamination

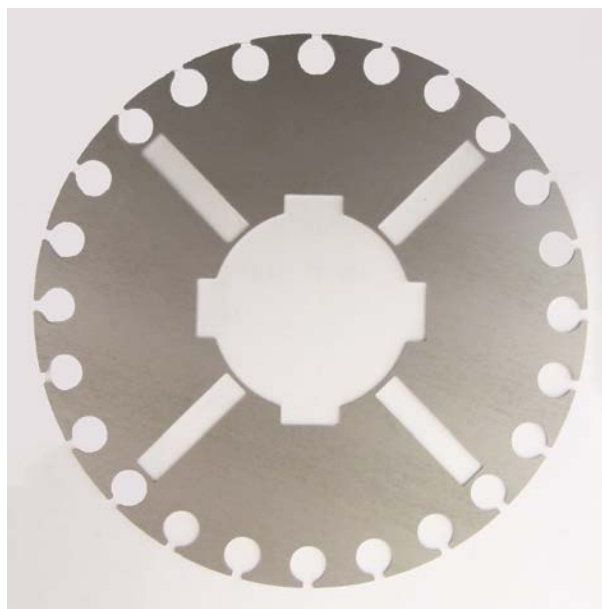


Figure 5.10: Photo of rotor lamination manufactured by Actom

According to Actom the laminations manufacturing tolerance is the same as for the stator laminations (0.1 mm). The large number of small movements needed to cut the lamination makes the laser cutting less accurate. Figure 5.11 and Figure 5.12 shows some of the faults found on the laminations. The

manufacturing faults can be compared with lamination in Figure 5.10. Several burn marks were found on the lamination edges; this is accredited to the starting point of the laser where added heat needed to be generated to burn through the steel. Other laminations had an irregular outer diameter finish, but the biggest and most frequent problem was that the magnet slots were not centred on the lamination.

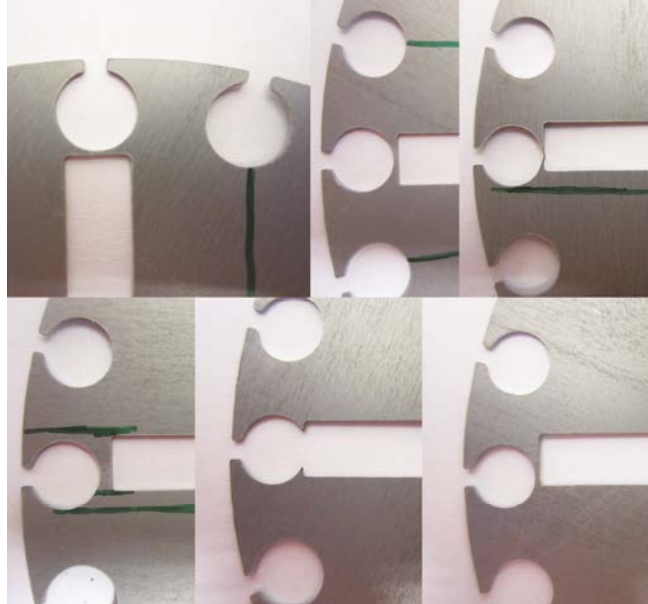


Figure 5.11: Images of defaced laminations

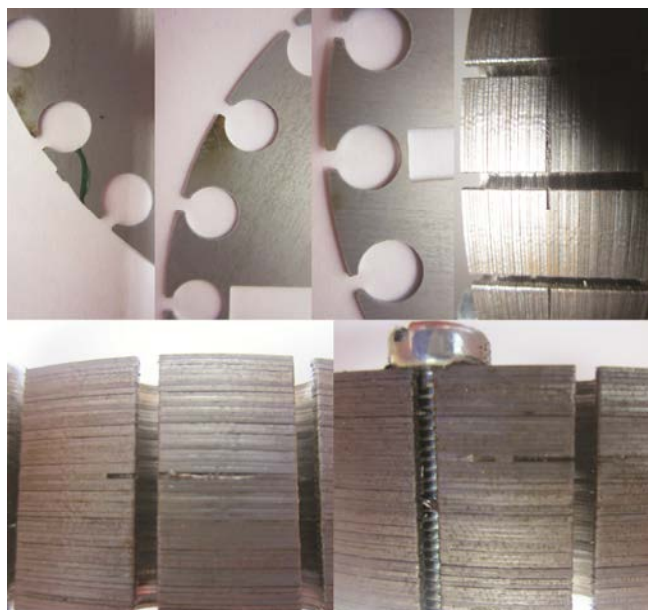


Figure 5.12: Images of defected outer diameter edges

Of the three lamination manufacturing faults, the-off centre magnets slots pose the biggest problem during rotor stack manufacturing as this leads to the rotor bar slots not lining up for the rotor bars to be slotted in during assembly.

5.3.2 Permanent magnets

The permanent magnets were ordered from Bakker Magnetics in the Netherlands. Various material types and grades can be ordered. The magnets are manufactured to the required dimensions in accordance to specifications found on their website (www.baktermagnetics.com).

As only 4 magnets are needed for the prototype and a minimum of 20 magnets is needed for an order, it was decided to segment a magnet into 4 smaller magnets. Thus 16 magnets are needed. The added benefit of incorporating segmented magnets is that the magnet can be handled more easily during machine manufacturing. By using segmented magnets and placing the minimum order of 20, there are spare magnets available in the event of a magnet braking during machine assembly. Table 5.6 contains the information of the PMs used for the prototype.

Table 5.6: PM material info

Component	Specification
Dimensions (l x t x h) [mm]	28.75 x 6 x 26
PM material	Neodymium Sintered
Grade	N 33 M
Coating	Epoxy (Ni + Cu + Epoxy)

Figure 5.13 is an image of the PMs. The magnets are stacked with the magnet poles lining up. Between each magnet a plastic spacer is placed so the magnets can be easily separated.

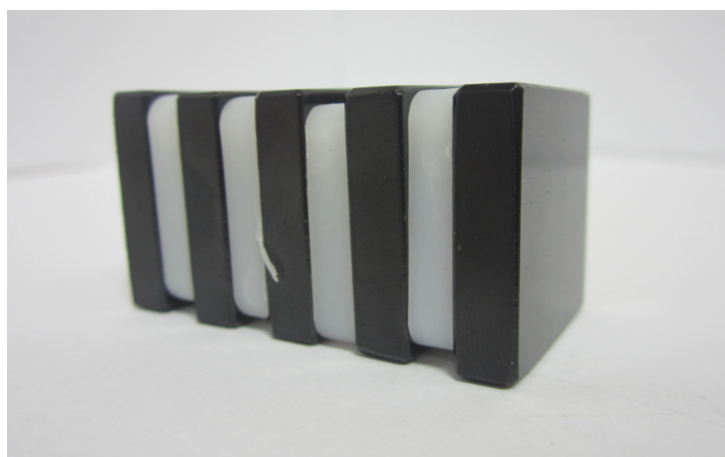


Figure 5.13: Image of the PMs as manufactured by Bakker Magnetics

5.3.3 Rotor shaft and bearings

The shaft for the prototype is based on the dimensions of the Weg W22 7.5 kW IM's shaft. The majority of the shaft dimensions were measured on the shaft that was fitted in the machine frame received from Weg. However the centre section on which the rotor stack is placed has a diameter smaller than that of the

original shaft. Furthermore a non-magnetic material had to be used to reduce the leakage flux through the rotor shaft. Also located on the centre section are four key notches. This is to aid in transferring the magnetic torque generated by the machine onto the load via the shaft and to keep the stack from revolving around the shaft.

To select the correct material and to verify that the shaft can operate within and transfer the torque of the machine, the design was done by a mechanical engineering student. A third year student designed the final shaft as shown in Figure 5.14. His shaft design is as in Appendix F. The shaft was manufactured from SAE 304 stainless steel, the keys are mild steel.

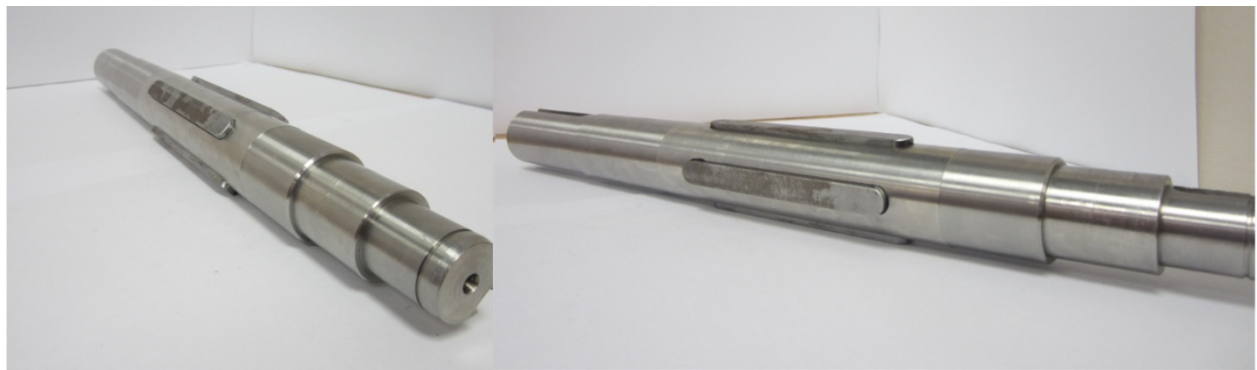


Figure 5.14: Image of stainless steel shaft

The bearings size information can be found on the relevant datasheet on Weg's website. The bearings can only be fitted on the shaft once the rotor stack is placed in the shaft.

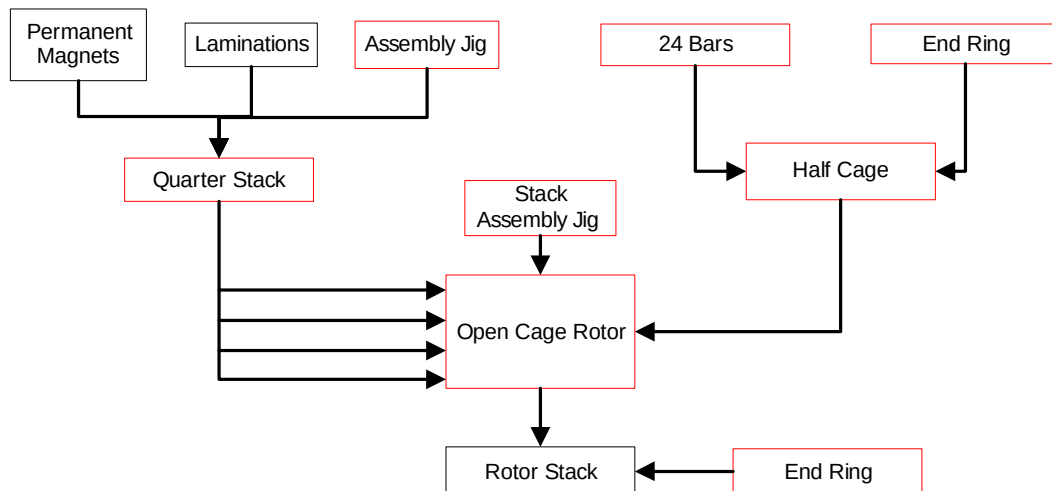
5.3.4 Rotor assembly

This section focuses on the rotor stack assembly and the rotor assembly as indicated by Figure 5.1. The main focus of this section is on the manufacturing of the rotor stack and how the various sub-components are combined and in what order and method they are used. Dimensional deviations from the design as in Chapter 3 are also listed.

During the rotor stack manufacturing stage, two methods were used. The first method, Method A, was in theory and in preliminary testing a good option to manufacture the stack. During the actual manufacturing several problems occurred and this option was abandoned. From the lessons learned in Method A, Method B was compiled and new components were manufactured.

Method A is discussed to aid in the planning of future machine manufacturing. This method or something very similar was previously used by other students at the NWU on a high speed IM and thought to be a good reference for the machine.

Figure 5.15 is a flow diagram indicating the assembly process for the rotor stack. The blocks in red are components or assemblies that have not been discussed in this chapter. An image of each of these components as well as a brief discussion is listed under this section. The assembly method is derived in two parts, the manufacturing of the half cage and the quarter stacks. Once these two components are complete the open cage rotor is assembled with the aid of an assembly jig after which the second end ring is welded in place.



Half Cage:

The half cage consists of the 24 aluminium bars and one of the aluminium end rings. To construct the half cage a reduced edge was turned into the bar at one end with a diameter of 6 mm, the end of the bar was also chamfered. This was to aid in welding the end ring to the bar. The corresponding end ring's fitting holes has a diameter of 6 mm with a sliding fit tolerance in terms of the bars. At the welding side of the end ring each hole's edge is chamfered, thus when the bar is inserted into the hole, a welding channel is formed between the two chamfered edges. The bar's length was increased from the required 135 mm to 140 mm to ensure that the bar is outside the end ring welding edge. The excess aluminium will be removed once both end rings are welded in place. Figure 5.16 and 5.17 are images of the half cage and its components.



Figure 5.16: Images of rotor end rings and cage bars



Figure 5.17: Images of half cage

During the manufacturing of the half cage several things were noted. For a single bar to fit through a quarter stack cage slot, the bar's diameter had to be reduced from 7.5 mm to 7.3 mm. The reduction made for a good sliding fit of the bar into the rotor cage slot. The other point of interest is on the welding end of the half cage. The chamfers on both the bars and end ring was not big enough which made welding difficult.

Quarter stacks:

To assemble the quarter stacks, a basic jig was constructed from three 5 mm Perspex sheets. The purpose of the jig is to house the four PMs and keep them in place so the rotor laminations can be placed over them one by one until the laminations provided sufficient hold on the magnets. As all four magnets are in contact with the lamination edge, the laminations tend to lodge themselves in such a manner that it was difficult to press the lamination down over the magnets; the jig can also be used to apply equal force over the lamination. A single lamination was placed under the jig; this was used to provide added rigidity to the magnets and to keep the magnets from falling out during the early stages of assembly. Figure 5.18 is

an image of the Perspex jig with the four PMs in place. For the design topology, the flux producing faces facing each other have to repel each other. To check that the magnets' polarities are correct, the magnet being installed must be brought closer to the already installed magnet. If the magnets attract each other just turn the magnet face around. Great care must be taken during this step as the attraction forced between the two magnets is high.

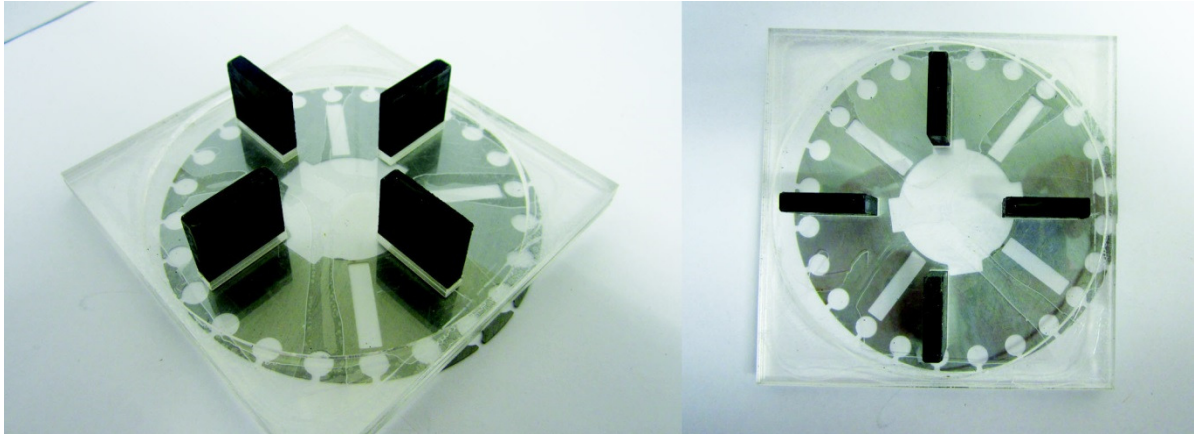


Figure 5.18: Image of Perspex PM placement jig with magnets

Once the four magnets are in place in the jig, the laminations are placed over the magnets one by one until the laminations span the entire length of the magnets. At this point, the laminations need to be compressed as there are very small gaps between several of them. To compress the laminations eight M6 nut and bolts are used with one M26 nut and bolt pair. With the M26, two wide flange washers must be used. The washers had to be adapted so they only press down on the lamination and not the magnets when tightened. The bolts must be placed as in Figure 5.19 and in the same order and rotor slots, top left to bottom left.



Figure 5.19: Image of quarter rotor stack assembly guide

The bottom right image is of a phenomenon that occurs when the magnets are in the slots (in the figure only one magnet is inserted for illustration proposes). The magnetic forces of the magnets equally spaced the laminations over the length of the magnets. As more lamination is placed on the stack the space between two laminations is reduced to the point where there is no space between them. Once the laminations span the entire length of the magnet, the magnetic force forces the laminations on both ends out of position so that they don't form part of the stack. This however is almost completely eliminated once the stack is compressed with the technique shown in Figure 5.17 and additional laminations are placed on the spaces gained by the compression.

Stack Assembly Jig:

To assemble the four quarter stacks and the half cage a jig was used. Figure 5.20 is an image of the jig. The jig consists of a bottom housing plate, centre alignment shaft and a threaded rod with a grooved edge steel plate situated inside the alignment rod. The purpose of the jig is to apply pressure on either the stack with or without the top end ring to ensure that the quarter stacks are as close as possible to one another before the end ring is welded in place.

One of the key design features of the rig is the grooved edge of the steel plate. The grooved edge ensures that when the plate is placed on the end ring, the plate is centred on the end ring ensuring equal pressure over the entire end ring. The other feature is the detachable centre alignment shaft. By removing the shaft or changing it with a shorter shaft the pressure plate can be used to gradually press a quarter stack down into position.



Figure 5.20: Image of rotor stack assembly jig

Assembly steps of Method A:

After all the components have been assembled and manufactured the first step is to place the half cage into the jig as indicated in Figure 5.21. The image on the left indicated the fit of the end ring inside the jig. The centre alignment shaft can be removed.

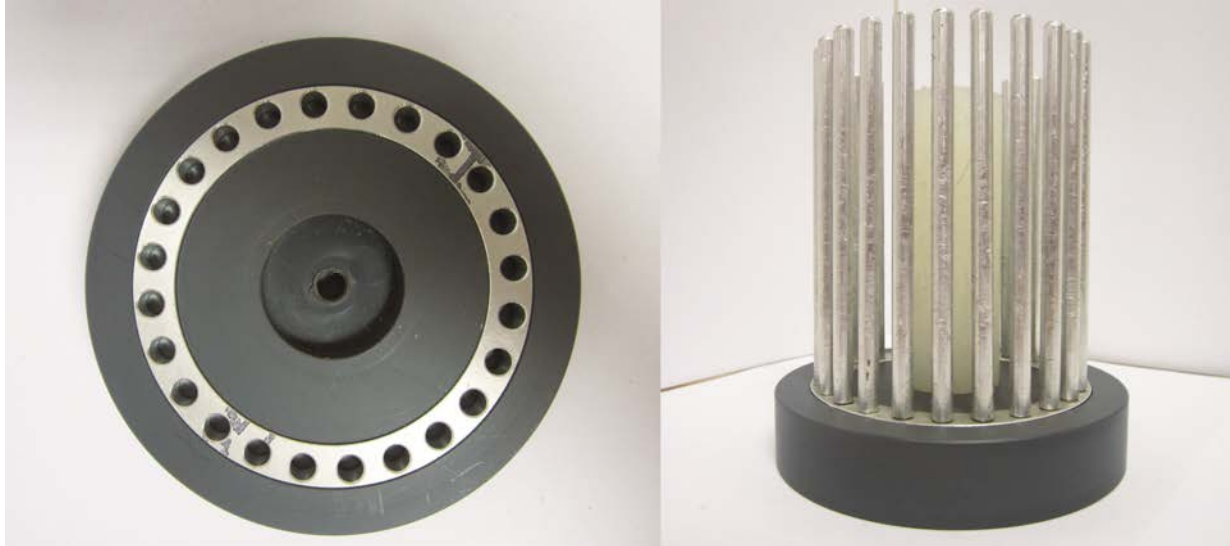


Figure 5.21: Image of half cage in assembly jig

Once the cage is in the jig, the next step is to slide a quarter stack over the cage. Here the chamfers on the bar edges make it easier to slide the quarter stack over the top ends of the bar. To slide the stack over the cage, the bolts in the rotor bars have to be removed. The centre clamp must be left in place. This is done with each quarter stack.

When all four quarter stacks are placed in position, the end ring must be added. To press the stack to the required length, the top plate is placed on the end ring and the nut is tightened to apply pressure on the stack. The nut is tightened to the required stack length. Once the stack length is correct, the end rings are welded in place.

Problems with assembly Method A and lessons learnt:

The assembly of the quarter stack posed no great problems. The biggest problem was that the magnets de-aligned with respect to the perpendicular building surface. To correct this problem a plastic hammer was used once the stack was almost done. The stack must be placed on a flat surface and lightly hammered until all four magnets are flush with the lamination surface.

The biggest problem with Method A occurred when sliding the stack over the cage bars. The stack slid smoothly over the rotor bars and all the laminations were still intact. However two thirds down the bars the laminations started to flare and the friction caused by the flaring against the aluminium bars caused the stack to become stuck in the position. The stack could not be pressed back as the laminations

deformed the bars. It was at this point that it was decided to forfeit this method as it would not be possible to get all four stacks on the cage due to the lamination flaring.

From this method it is clear that not all of the bolts used to hold the stack together could be removed. Thus at least the four bolts that are in line with the magnets must be left in, as the magnetic forces at these points are the highest. Furthermore it would be wiser to insert the bars one by one in the slots instead of assembling a half cage first. This would reduce the risk of a bar lodging itself in a position and if this happens only one bar has to be removed which is much easier.

5.3.4.2 Method B

For Method B the main idea behind the assembly of the stack is similar to that of Method A. The main difference is that the rotor bars are inserted individually into the slots and not all at the same time. For the slots containing bolts, the bars will only be inserted once all four quarter stacks are in place. Figure 5.22 contains the construction flow diagram for Method B.

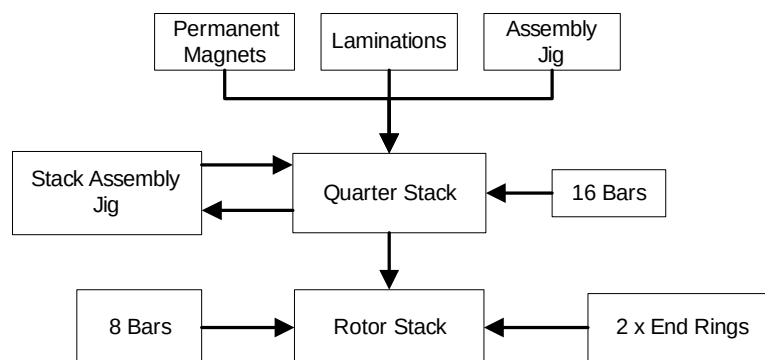


Figure 5.22: Method B assembly flow diagram

To assemble the quarter stacks the same technique is used as in Method A. Once all four stacks are complete the next step is to start assembling the stack. The technique to do this is very basic and must be repeated several times.

First remove the bolts on the d-axis as well as the centre bolt and both washers. Next insert the centre alignment shaft as well as a threaded rod long enough to span two stacks including the space between the two stacks due to the nuts of each stack. Ensure that the nuts of the bolts are towards the greater end of the threaded rod. Once this is done the bars must be inserted in the 16 open slots. The bars dimensions are the same as in Method A; the chamfers on both ends were increased. The entire sub-component can be placed on a metal surface to short circuit the magnetic flux thus making assembly easier.

Next, place another quarter stack in top of the structure constructed above ensuring that the nuts face towards the first stack's nuts. Once the stack is in place tighten the d-axis nuts. Next remove the inner nuts of one stack by using a spanner to slide the nut out between the stacks. Once both the nut and bolt are

removed the d-axis nuts must be tightened again. Now the nut and bolts of the other stack must be removed. Once they are removed threaded rod spanning both stacks must be inserted in the slots. Ensure that one side of the stack's nuts are flush with the threaded rod. Figure 5.23 contains images of the steps described above



Figure 5.23: Photos of rotor assembly

To include the two remaining quarter stacks in the final stack they must be fitted in the same manner as described above. Figure 5.24 contains images of the remaining quarter stack assembly. Between the two quarter stacks for the remaining stacks an extra lamination was placed. This was because there was space for an extra lamination in both instances.



Figure 5.24: Photos of rotor assembly

When the four stacks are in place the end rings need to be placed in their respective positions. One of the end rings must also be placed in the assembly jig. From this point on, the assembly method is the same as in Method A but with the difference that now both ends need to be welded. Figure 5.25 contains images of the final stages of the stack assembly up to a point where it is possible to weld the end rings.

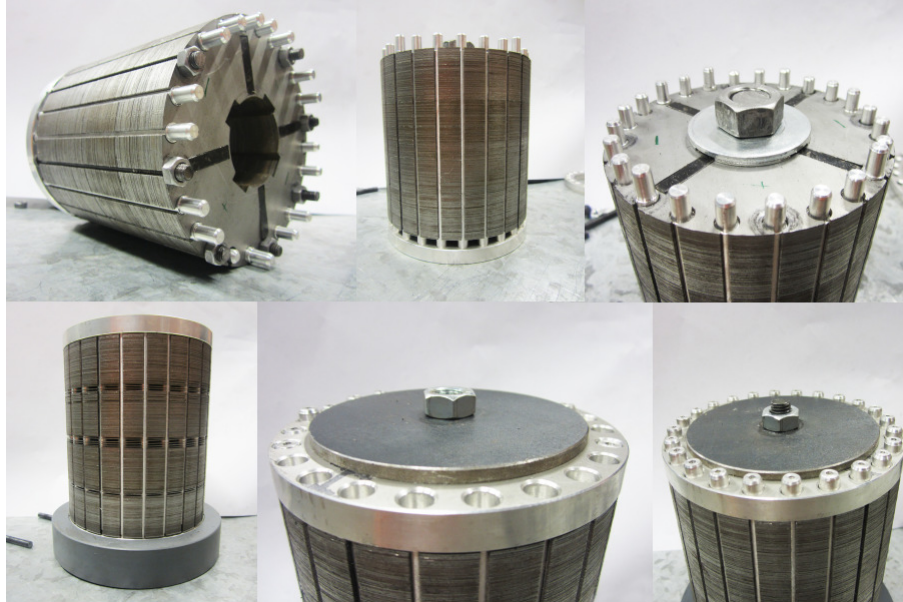


Figure 5.25: Images of rotor stack in jig

Once both the rotor stack and shaft is completed the stack and two bearings can be pressed onto the shaft. When the stack is pressed onto the shaft the rotor stack has to align with the stator stack. This is done by measuring the distance from the bearing housing of the end cap up to the stator stack. This distance is then marked on the shaft from where the bearing is placed.

Once the rotor stack is placed on the shaft alignment needs to be checked. During this time it was noted that the assembled rotor could not fit inside the stator. The rotor stack became slightly warped during the welding of the end rings. As the air gap is 0.5 mm even a slight deviation on the outside diameter of the stack will cause the rotor not to fit. This problem was easily fixed by machining the outside diameter to provide the correct fit. The machining of the rotor must be accurate because if the air gap is more than 0.5mm the flux, back-emf and torque are influenced negatively. The final machined rotor is shown in Figure 5.26; the bearings have not yet been pressed onto the shaft.

During the welding, it was very difficult to weld the bars situated on the q-axis. It seems that the magnetic field of the magnets forced the arc of the welder away from the welding surface. This can also be seen in Figure 5.26

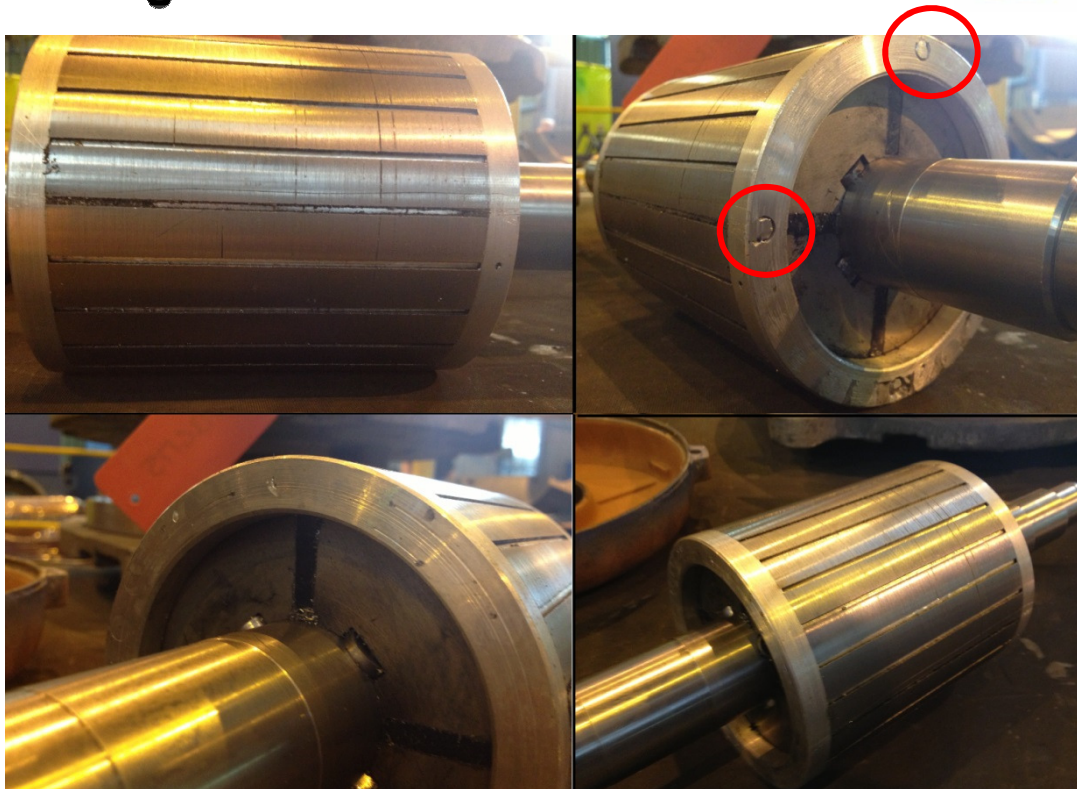


Figure 5.26: Machined down rotor

Once the bearings were pressed onto the shaft the machine was assembled. After the test is completed an information plate will be manufactured containing the data normally found on all machine information plates. Figure 5.27 is photos of the final machine.

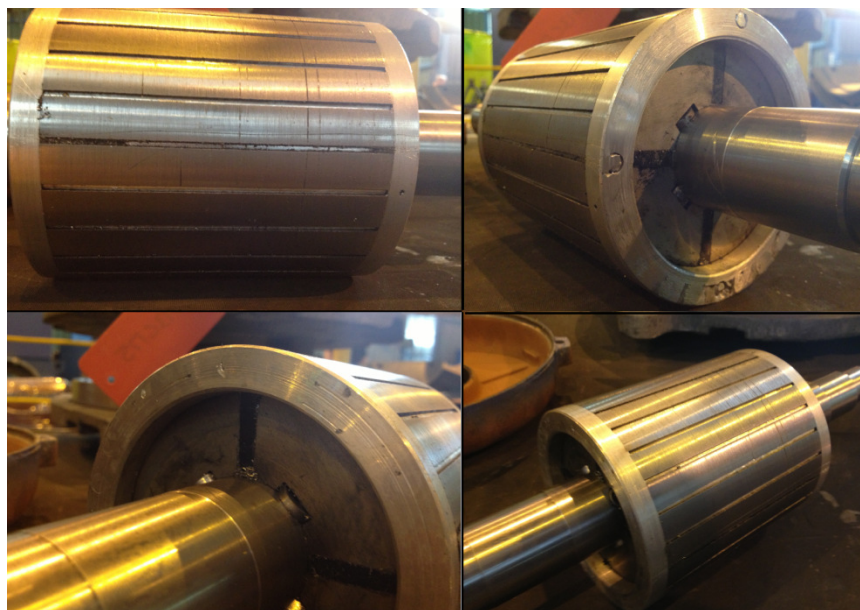


Figure 5.27: Images of completed LS PMSM prototype

5.4 Manufacturing cost

This section contains the overall cost associated with the manufacturing of the prototype. Several of the components were sponsored by various companies or were done at a reduced cost.

Table 5.7 contains the information regarding the stator manufacturing cost. The 132S frame was a 5.5 kW IE2 IM machine that was sponsored by Zest motor group. Marthinusen & Coutts only charged for the labour on the wiring and not the material used. This amount was included in the overall amount to use their onsite test facilities.

Table 5.7: Stator manufacturing cost

Component	Total	Manufacturing time	Quantity
Stator Laminations	R 7485	4 weeks	250
Stack assembly	R 4430		1
Wiring & VPI	Sponsored	2 weeks	1
132 S Frame	Sponsored	-	-

Table 5.8 contains the rotor manufacturing cost information. All the manufacturing was done in-house at the university except for the laminations that were outsourced to Actom.

Table 5.8: Rotor manufacturing cost

Component	Total cost	Manufacturing time	Quantity
Rotor Laminations	R 9760	4 weeks	2 x 230
PMs	R 3440	6 Weeks	40
Shaft	R 1990	1 Week	1
Bearing	R 256	-	2
Keyway steel	R 60		5
Rotor cage	R 2100	1 Week	2
Assembly jig	R 300	1 Week	1
Other			

The cost with regards to testing the machine at Marthinusen & Coutts was R2750 but as stated earlier this also included some labour cost.

Several of the items listed in Table 5.7 and Table 5.8 were purchased in larger quantities than needed. This was done either because there is a minimum order requirement or to accommodate any manufacturing and assembling faults or problems.