2

Chapter

Mechanical design considerations

Chapter 2 focuses on the mechanical design considerations of a high speed induction machine rotor section. The different types of rotor constructions are compared in terms of mechanical limitations as well as electromagnetic performance. A detail discussion on the squirrel cage design, which includes manufacturing and assembly procedures, is described. Core/shaft connections are discussed and the effect of the elevated operating temperature is investigated. The terms "manufacturing" and "assembly" are defined in terms of this document, and the importance of design for manufacturing and assembly is emphasized. The chapter is concluded with a critical overview of the literature discussed throughout the chapter and some initial rotor design decisions are presented.

2.1 Literature overview

Developing a high speed induction machine rotor involves an intricate iterative design process in terms of mechanical and electrical considerations. Consequently an obvious starting point is looking at work done on similar design-problems and applying it to the current application. This section gives an overview on the literature used to formulate an optimal design solution. Figure 2-1 shows a brake down structure of the design considerations found from literature that need further discussion.

Using the design specifications given in Table 1-1 as the starting point, the relevant literature on the mechanical design of high speed induction machine (IM) rotors is revealed. The literature mainly focuses on the mechanical and to a lesser extent the electrical design of the rotor. These references [7] [9] [10] are used as the basis of the literature study and provide insight into specific issues to be addressed in the mechanical design of a high speed IM rotor. The issues include; Magnetic core selection, high electrical flow-path design, shaft design, shaft magnetic core connections, thermal effects at high temperature operation as well as manufacturing and assembly procedures.

The literature [2] [24] [25] shows that two types of magnetic cores are mainly used in an IM namely; Solid and laminated rotor cores. Both the mechanical and electrical advantages and limitations are investigated.

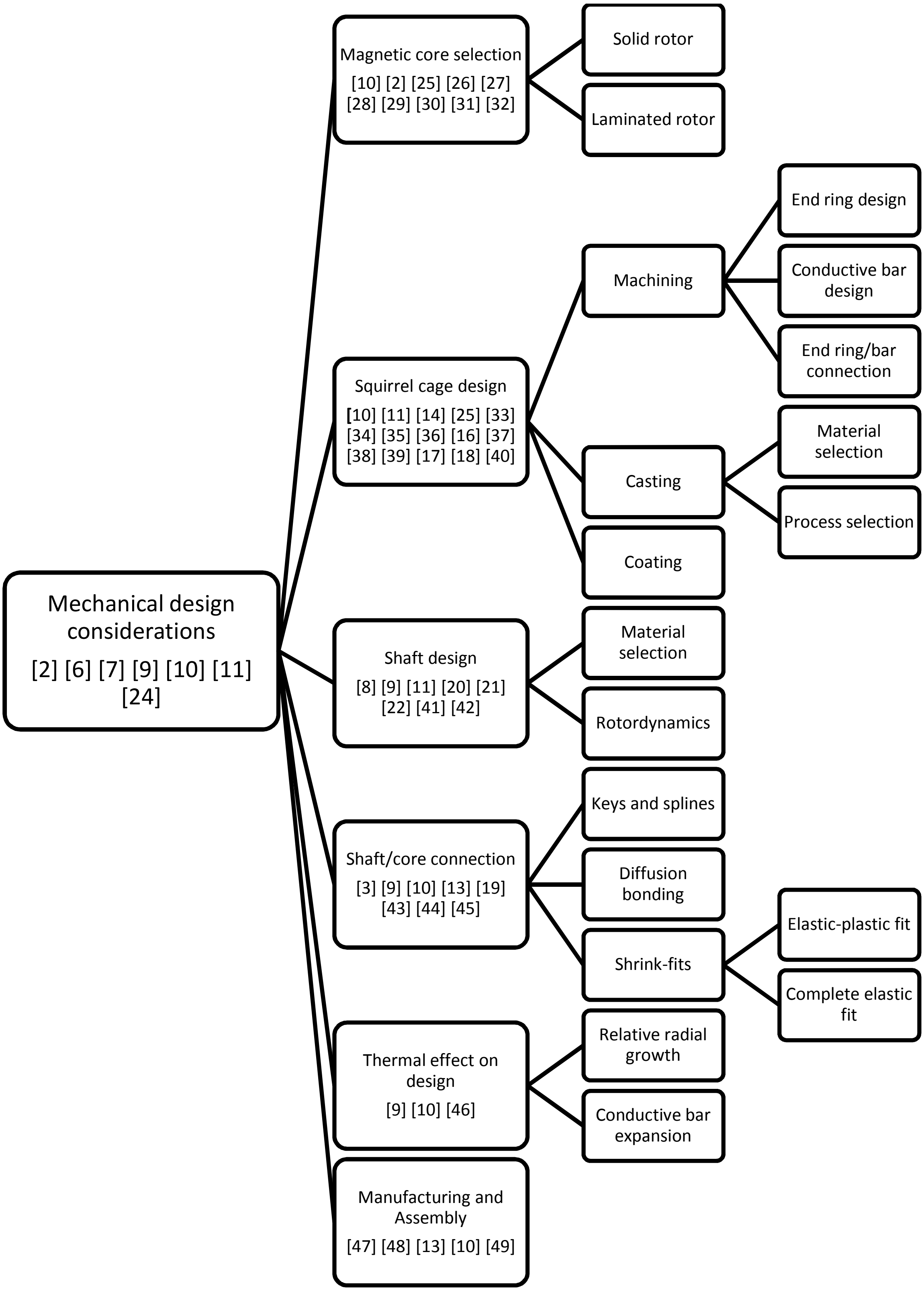

Figure 2-1: Mechanical design considerations detail breakdown

It is seen from the literature [24] [26] [27] that an increased electromagnetic efficiency can be achieved by incorporating a low resistive electrical flow path into the magnetic core. This can be in the form of a high conductive coating, casted or machined squirrel cage.

Although the rotordynamic analysis and shaft design is omitted from this document it is shown to form a critical part of a variable speed rotor design and does affect the rest of the design [8] [9] [20].

After selecting the appropriate magnetic core and rotor cage, the components will have to be connected to the shaft. In high speed application this is a critical consideration for the mechanical design due to the high centrifugal loads [3] [9] [10].

During assembly of the components, depending on the assembly procedure (shrink fit, diffusion bonding, welding etc.) temperature gradients will cause material stresses and will have to be managed. The operation of the machine at elevated operating temperatures will also contribute to material stresses and loss in contact due to radial growth [9] [10].

The mechanical integrity of the rotor as well as the electromagnetic efficiency depends largely on the materials selected for each component. The materials selected will also influence the manufacturing processes used to form the components as well as the assembly procedures used. The literature [10] [13] [28] describes the importance of material selection as well as manufacturing and assembly processes and considerations.

2.2 Induction machine rotor construction

From the literature as shown in section 1.3 and 1.4 selecting an optimal magnetic core can only be achieved when both mechanical and electromagnetic performance is considered. This section shows and compares two types of solid rotors and a laminated rotor.

The solid rotor can be made of a single piece of ferromagnetic material where the shaft and magnetic core is one component or the core could be a sleeve connected to the shaft. Solid rotor machines can be operated at very high speeds with no rotor dynamic problems due to the rigid rotor. Rotational speed is only limited by the maximum allowable stress in the material. However, the mechanical benefits come at a price, which is very poor electromagnetic performance [2].

In the case of a solid rotor the solid ferromagnetic core forms the electric and magnetic circuits. When high frequencies are applied like in high speed applications eddy-currents are induced in the magnetic core. Eddy-currents push the induced magnetic field out of the rotor therefore forcing the magnetic flux to the surface. The result is magnetic saturation and the inner part of the rotor material cannot be utilized. From this it becomes apparent that for an induction machine to have a good efficiency the rotor should have both a high permeability flux path and a low resistive electrical flow path. This is very difficult to achieve with a rotor consisting of only one material, therefore, these functions are performed using two different components made of appropriate materials [11]. With this in mind current rotor designs are considered and detail on the solid coated, solid cage and laminated cage rotors are discussed.

2.2.1 Current rotor design solutions

SatCon [10], a high speed machine solution company, design and manufacture high speed induction machines for different applications. One particular induction machine application is a turbine alternator. The 60,000 r/min machine with a rotor OD of 110 mm is subjected to material stresses above 1450 MPa at the ID of the core. The high stress rule out the use of a laminated core, and a solid core is the only option for this design. The material used is Aermet 100 which has a tensile yield strength of 1725 MPa and is sufficient for the application. Due to the toughness of the material, Electric Discharge Machining (EDM) is used as the finishing manufacturing process, more detail on this manufacturing process is presented in section 2.6. After manufacturing the core is shrink fitted onto the shaft, made of AISI 4340 and manufactured through centerless cylindrical grinding. However, due to the relative slow material removal processes (EDM and grinding), this production process is not an option for high volume production. Therefore in 1994 C.P. Brown proposed a modified design to optimize the manufacturing, for a high volume production line at SatCon. The conclusion was that the core made of Aermet must be casted using investment, sand, ceramic or resin mold casting methods. The core will have to be an open slot magnetic core to ensure no voids or defects due to the casting process. The core/shaft connection process recommended is low temperature diffusion bonding and will be discussed in more detail in section 2.6. Stainless steel 410 is selected for the shaft material and manufactured using centerless grinding. The reason for stainless steel 410 is due to the compatibility with the Aermet in the diffusion bonding process.

In another rotor design, M.T. Caprio, V.L. John and J.D. Herbst [9], describe a laminated rotor core in terms of material selection, core/shaft connection and strength analysis, Figure 2-2 illustrates the design. The rotor core length/diameter ratio is derived from the torque required and the material and rotordynamic restrictions. The core OD is calculated to be 364 mm with a rotor speed of 15 000 r/min, translating to a surface speed of 286 m/s.

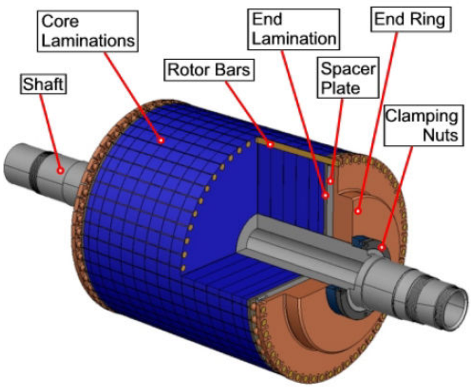

Figure 2-2: M.T. Caprio, V.L. John and J.D. Herbst, rotor configuration [9]

The core/shaft connection selected for their design is an interference fit. Due to the large OD and high operating speed, resulting in a very high surface speed, a large interference fit is required to secure the core to the shaft throughout the operating range. Consequently, the core is subjected to high tangential stresses due to rotation as well as the large interference fit. The authors show that conventional silicon electrical steel materials used for core laminations such as the AISI M-15 to M-47 series will not adhere to the stringent mechanical strength requirements. High strength AISI 4130 alloy steel was selected instead and after heat treatment a yield strength of 1241 MPa is obtained, which was sufficient for the application. The 0.35 mm laminations were laser cut and coated with a C5 insulating coating to reduce eddy current losses even more. The designers selected a heat treated AISI 4142 alloy for the hollow shaft. It is stated that the stresses at the core/shaft interface due to the interference fit is reduced by the hollow shaft. The reduction in stress is due to the hollow shaft being more compliant than a solid shaft. They also claim that the reduction in mass due to the hollow shaft effectively stiffens the shaft and increases the bending modes.

W.L. Soong, G.B. Kliman, R.N. Johnson, R.A. White and J.E. Miller [7] present a novel high speed induction machine rotor design. The 51 mm diameter laminated cage rotor operating at 50 000 r/min is shown to have a considerable amount of mechanical design challenges. The material selected for the laminated magnetic core was an un-coated high-silicon content, non-orientated steel sheet of 0.457 mm thickness. The sheet was rolled to a desired thickness of 0.356 mm at which point the material was extremely brittle. Different heat treatments were investigated to establish the optimal rotor lamination material properties, with the results illustrated in Figure 2-3. The material properties required is high strength and ductility mainly due to the interference fit and high centrifugal forces.

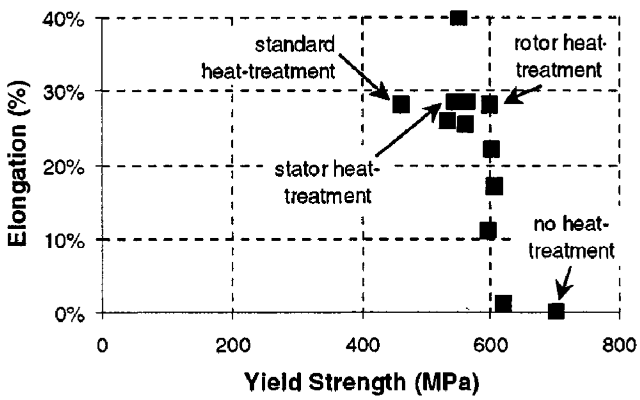

Figure 2-3: Rotor lamination material's tradeoff between strength and ductility [7]

The rotor laminations were laser cut with an undersized ID, bar slots and oversize OD from the brittle lamination sheet. The laminations were then heat treated and the ID machined. After assembly of the magnetic core and shaft the rotor's OD was machined to size. Extensive FEM stress calculations were done to obtain the optimal bar diameter and bar slot position. The results show that the maximum stress is found at the root and tip of the bar slot and even higher than the stress at the ID of the magnetic core [7].

The following section describes three rotor types in more detail in terms of their mechanical and electrical advantages and shortfalls. In conclusion Table 2-1 shows these three rotor types with their speeds achieved.

2.2.2 Solid coated rotor

Solid coated rotors utilize a conductive material coating on the outer surface of the rotor as the low resistive flow path illustrated in Figure 2-4. The coating replaces the squirrel cage and covers the entire magnetic core surface therefore acting as both the conductive bars and the end rings. This configuration allows for extremely high speeds due to the rigid rotor and a high strength bond achievable between the solid rotor and a copper coating of about 100 MPa [24].

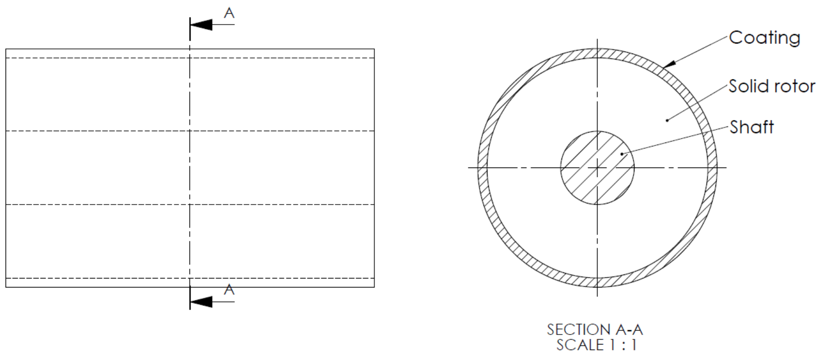

Figure 2-4: Solid coated rotor illustration

In a comparative study [24] the thickness of the coating is varied. The results show that the stress in both the solid core and coating decreases as the coating's thickness is increased. While the maximum operating speed is increased with an increase in coating thickness, the air gap between the stator iron and the rotor iron is increased. The result is higher magnetization currents and an increase in resistive losses in the stator windings [11].

2.2.3 Solid cage rotor

Solid cage rotors combine a rigid solid rotor to enable high speed and a squirrel cage made of good electrical conductive material for improved electromagnetic performance. As in the solid coated rotor the flux penetration depth is limited in the solid cage rotor. Adding axial slits to the core will improve the flux penetration depth and utilise the solid rotor and squirrel cage more effectively [2]. Detail on the squirrel cage design is given in paragraph 2.3. The squirrel cage mounted with open slots as illustrated in Figure 2-5 is one of many design configurations [2] [26]. The open slots will enable easy machining and both milling and broaching operations can be used for this application.

Alternative configurations show the bars to be situated below the rotor surface, however, this is difficult to manufacture [25] [27]. Typical manufacturing method used will be wire electrical discharge machining (EDM) or spark erosion. EDM is based on erosion of metals by spark discharges. Typical cutting rates for a 50 mm thick D2 tool steel is 18 000 mm^2/hr and for a 150 mm thick aluminium it would be about 45 000 mm^2/hr. This translates to a linear cutting speed of 360 mm/hr and 300 mm/hr respectively [13]. Due to this slow cutting rate the process can become very expensive. Considering a 125 mm diameter rotor with twenty four 10 mm bar slots the linear cutting length would be ± 5 m. Take an axial length of 150 mm and an average cutting speed of 25 000 mm^2/hr, then the time required is 30 hours without setup time. The rotor will also have to be slitted if the core is to be machined in one step.

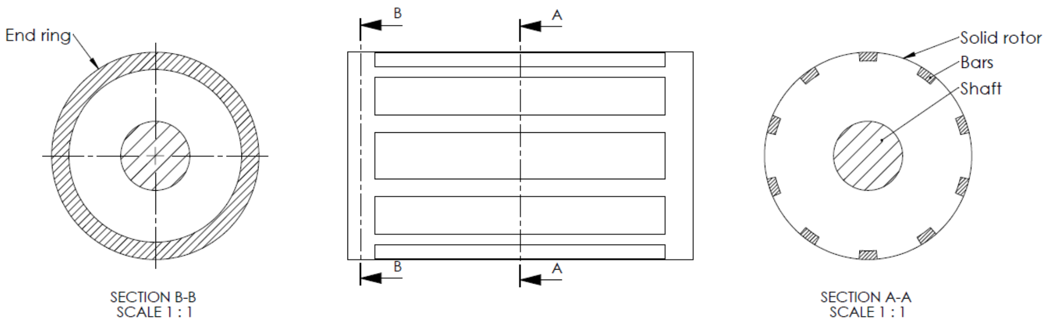

Figure 2-5: Solid cage rotor illustration

2.2.4 Laminated cage rotor

Laminated cage rotors consist of a stack of ferromagnetic laminated thin discs making up the core and a cage made of non-ferromagnetic good conductive material, as illustrated in Figure 2-6. The laminated discs are punched or laser cut depending on the quantity and quality required. Punching only becomes viable at large quantities due to the cost of dies. Laser cutting provides a rough surface finish and relative low dimensional accuracy and might have to undergo further machining where surface finish and dimensional accuracy is crucial. Accurately assembling the individual lamination discs can also be problematic, therefore machining the assembled lamination stack will eliminate this problem. However, due to the axial length of the rotor stack accurate machining of the bar slots is seemingly impossible as will be described in the first iteration manufacturing procedure that was followed. Wire EDM can be used to machine the assembled lamination stack with great accuracy. Due to the discs being electrically isolated from each other it will have to be electrically connected, this can be done using laser welding, however, the axial length is the limiting parameter. The cutting rate of wire EDM will be very slow if at all possible adding extra costs.

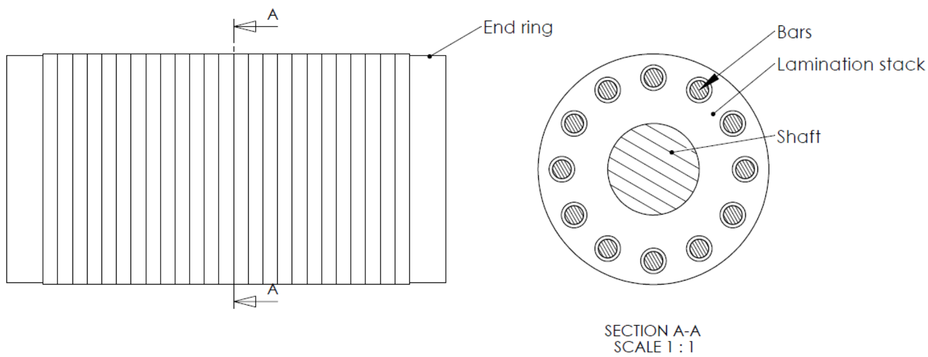

Figure 2-6: Laminated cage rotor illustration

The laminations limit eddy-currents much the same as a slitted solid rotor, however, the laminated core is much more effective. The addition of axial slits in the laminated core further improves electromagnetic performance [29]. With the increased flux penetration depth the machine becomes much more efficient.

Conductive bars are shown to be circular in Figure 2-6, however, other geometries as shown in [29] [27] [30] can also be considered. The choice of conductive bar and core slot geometry will depend on both stress analysis and electromagnetic performance.

Lamination material is shown to be one of the limiting components of a high speed laminated rotor in terms of mechanical strength [10]. Traditionally used Silicon-iron alloy lamination material has relatively low yield strengths of less than 400 MPa [31]. However, high strength Cobalt-iron alloys with high yield strength of 800 MPa [32] is available. Some motor manufacturers manufacture their own lamination material [7] [9] [33] for high strength applications.

Figure 2-6 show that the addition of the laminations decreases the shaft diameter considerably therefore lowering the critical frequencies of the shaft. Some machines can be operated above their first critical frequency [34]. However, with variable speed drives that require a large operating speed range this is not advisable. Operating a laminated rotor above its first critical frequency can also cause rotor instability due to internal friction [22] [21].

2.2.5 Conclusion on rotor construction

It is apparent from the current design solutions is that a laminated core is always the preferred solution from an electromagnetic point of view. The literature shows that the designers would rather fabricate their own lamination materials to obtain the desired strength at the cost of electrical properties to enable high speed operation, before selecting a solid core. However, the solid core is probably the only option when very high speeds are required. Consequently it is essential that the designers decide whether the very high speed will contribute better to an application than a "slower" but more efficient rotor. Table 2-1 is a summary of the surface speeds (v_c) achieved by the rotors as discussed in the previous section. The rotors are listed from the fastest to the slowest surface speed achieved.

Table 2-1: Different rotor configurations and the speed achieved

v_c (m/s)	OD (mm)	Rotor type	Power (kW)	Reference
367	70	Solid coated	60	[11]
345	110	Solid caged	-	[10]
286	364	Laminated	2000	[9]
283	90	Solid coated	60	[11]
236	90	Solid caged	50	[11]
193	330	Solid caged	2610	[11]
185	118	Laminated	100	[11]
182	348	Laminated	6000	[11]
174	123	Laminated	100	[4]
168	80	Laminated	35	[11]
134	51	Laminated	21	[11]
131	50	Laminated	21	[7]

2.3 Rotor cage design

Section 2.2 shows that the addition of a low resistive electrical flow path to the rotor structure enhances the electromagnetic performance of the induction machine considerably. It is also shown that the cage rotor outperforms the coated rotor in terms of efficiency. Materials generally used for a rotor cage are aluminium and copper or for higher strength applications, aluminium and copper alloys. Although these materials have very good electrical properties they have relatively low mechanical strength and stiffness [14]. The result is an intricate design problem involving both mechanical and electrical design considerations. The following section gives more detail on current design solutions and mechanical design of the low resistive electrical flow path (rotor cage).

2.3.1 Current rotor cage design solutions

M.T. Caprio, V.L. John and J.D. Herbst [9] use a fabricated rotor cage for the low resistive electrical flow path, due to the insufficient strength of the casted aluminium or copper alloy cage. A round cross section is shown to be the preferred profile of the conductive bars, to eliminate stress concentrations at the contact area on the laminated core. The material selected for the conductive bar is a hardened Zirconium Copper (UNS C15000). The material is selected for its high tensile strength of more than 460 MPa and high electrical conductivity of more than 90% IACS (International Annealed Copper Standard). The design describes a novel end ring that fulfils both the electric and mechanical requirements for the high performance machine. As illustrated in Figure 2-7 the end ring's non-uniform section is specifically designed to allow bending of the end ring as illustrated in Figure 2-8. The bending is due to the radial and axial growth of the end ring and bar respectively, at high operating temperatures. The material selected for the end ring is a Beryllium copper (UNS C17510) with a tensile strength of more than 680 MPa and a conductivity of more than 60% IACS. The stress relieve cut between the rotor bar connections eliminate the addition of hoop stresses on the end ring/bar connections. The stress in the end ring/bar connection is further lowered by the addition of a ring boss feature as illustrated in Figure 2-9.

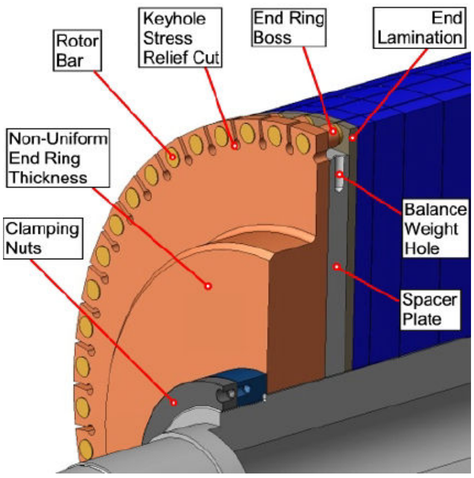

Figure 2-7: M.T. Caprio, V.L. John and J.D. Herbst, novel end ring design [9]

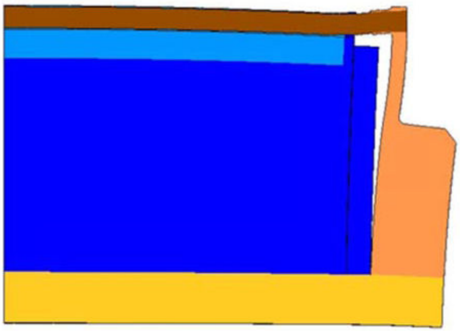

Figure 2-8: Exaggerated deformation due to temperature [9]

Due to the stress relieve cut in the end rings, a lower strength connection is required for the end ring/bar connection. Furthermore an end ring boss feature as illustrated in Figure 2-9 is employed to reduce the stress in the connection even more. The designers investigate a low temperature solder process that does not affect the material properties of the heat treated copper alloys. Multiple filler metals were tested to ensure low temperature solidification and adequate strength. Among them is a number of Au, In and Zn base fillers [9].

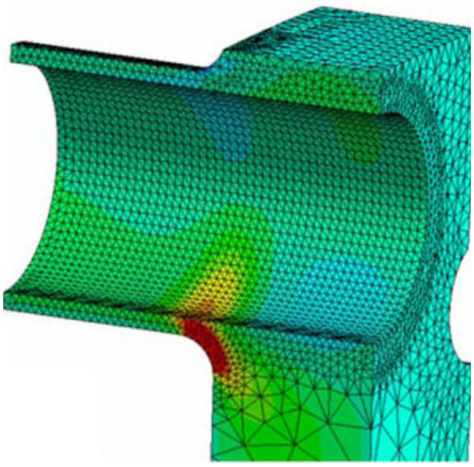

Figure 2-9: End ring boss feature [9]

SatCon [10] also uses a fabricated cage due to the low strength of the castable aluminium and copper alloys. The bars and end rings are machined to very tight dimensional tolerances form Glidcop®, a copper dispersion strengthened by aluminium oxide. Three variations to the material is available with the difference in the percentage Al_2O_3. The addition of Al_2O_3 lowers the thermal and electrical conductivity while increasing the strength. It is also very stable at high temperatures and suitable for brazing as well as cold working. Glidcop®AL-60 is the strongest of the three and is made up of 1.1% Al_2O_3 and 98.9% Cu, it has a tensile yield strength of more than 413 MPa and a conductivity of more than 75% IACS [35].

The design utilise press fits as the assembly mechanism for the cage. The bars are press fit into the core while the end rings are press fit onto the bars. The bar/end ring connection's electrical conductivity is ensured by brazing the connection with a silver-base filler alloy. However, to ensure the silver does not diffuse into the bar material and alter the desired material properties, the components are electroplated. This process further increases the complexity of the assembly and is not suitable for high production rates.

Research on optimising the manufacturing process at their facility was done and a revised manufacturing and assembly procedure is proposed. The research shows that both Glidcop® and Cr-Cu alloy is suitable for use in this high performance application. It is indicated that in order to simplify the manufacturing and assembly of the squirrel cage, it should be done using one process. This can be done by pressing Glidcop® powder into the slots and sinter it in place. Due to the core having open bar slots the powder will be able to be compressed isostatically. This could be done using a Hot Isostatic Press unit. The cage can then be diffusion bonded to the core and shaft. Due to the selection of Aermet 100 as core material, the high temperature manufacturing and assembly processes will have no effect on the core's material properties [10].

The design of W.L. Soong, G.B. Kliman, R.N. Johnson, R.A. White and J.E. Miller [7], also utilise a fabricated rotor cage. The cage acts as axial clamp to ensure no movement of the laminations while fulfilling its primary objective of conducting current. Due to this, a high strength material with high conductivity is required. Figure 2-10 shows typically used materials and the compromise that has to be made for high strength requirements. Glidcop® AL-15 was selected for the conductive bars due to the high conductivity requirements. The end rings are made of Glidcop®AL-60 due to its high strength and the fact that the lower conductivity could be countered by increasing the cross sectional area of the end ring. The manufacturing of the bars is an intricate process, where the Cu and Al_2O_3 powder is mixed and inserted into a Cu tube. The tube is heated and drawn to fuse the powder and the Cu tube is machined off.

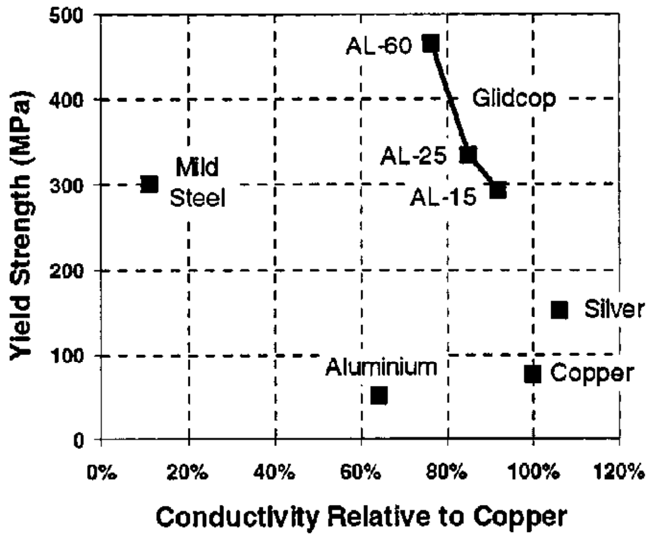

Figure 2-10: Rotor cage material trade off between conductivity and strength [7]

The selected bar/end ring connection is brazing and the connection type presents numerous problems, including: Flux entrapment creating stress concentrations and embrittlement of the Cu as a result of the silver migration. The brazing process is also limited to a relative low temperature, not to affect the material properties of the lamination material. Extensive testing was done to find the optimal brazing technique and 48 samples was brazed, sliced, polished and examined to ensure the integrity of the brazed joint. The preferred brazing technique is found to be, torch brazing where the two components have a small clearance, without nickel plating and using a low-temperature braze alloy with flux. The temperature of the laminations close to the end ring, while brazing, is critical and was monitored using thermocouples to ensure the temperature is under an acceptable level.

From the current solutions described above a better idea of what can be done is formed. The following section gives more detail on the mechanical implications of both the casted and fabricated squirrel cage designs. The discussion is in terms of material selection, manufacturing process as well as the types of connections available to both the bar/end ring and squirrel cage/shaft connections.

2.3.2 Aluminium and copper die cast squirrel cages

Traditionally used induction machine squirrel cages can be casted into the magnetic core. Once the cage has solidified the magnetic core is placed over the shaft and a shrink fit is used for the shaft/magnetic core connection. A typical casting method used is cold-chamber die casting [13]. In the case of a laminated core, special care should be taken in the assembly of the lamination stack before casting. Any burrs can cause turbulent flow of the molten metal which results in voids and irregularities. This can have a negative effect on machine performance, strength and reliability [10].

Aluminium alloys are widely used for the cage material in casting processes due to the relatively low melting temperature starting at T_m = 600 °C and relatively good electrical properties [14]. Aluminium alloys suitable for die casting is 360.0, 380.0 and 413.0 with an electrical conductivity of between 27 - 39% IACS, relatively low yield strength of between 145 -165 MPa and a machinability of between 40 – 50% compare to aluminium alloys [35].

Copper alloys has much better electrical properties, however, the melting temperature starts at T_m = 1000 °C [14] [15]. Low resistive copper casting alloys include UNS C81100, C81400 and C81500 to name but a view, with electrical conductivity of between 69 – 92% IACS, yield strength between 65 – 250 MPa and machinability between 10 – 30 % (free-cutting brass UNS C36000 = 100%) [35]. Heat treatment and the addition of alloys might increase the strength of the material, but an increase in electrical resistivity is expected. Heat treatment also presents a problem as the cage is casted into the magnetic core and heat treatment will influence the mechanical and magnetic properties of the core material. In the case of die-casting the die material also requires careful selection due to the high temperature operation. Pre-heating the die relieves tension in the die material due to the large temperature difference between the die and molten metal, limiting thermal fatigue [36]. Except for the die material, high temperatures will affect both the strength and magnetic properties of the lamination material, especially if the material used is in the annealed condition.

2.3.3 Manufactured aluminium and copper squirrel cages

The squirrel cage is made up of a number of conductive bars connected with an end ring at each end hence the name “squirrel cage”. The number of components can be between 10 and 30 per rotor, depending on the number of conductive bars. Manufacturing the components individually is therefore a timely and costly alternative. The components also require very tight dimensional tolerances to ensure rotor integrity and repeatability. Connecting the bars and end rings with a low resistive and rigid connection is also important to achieve good efficiency as well as rotor stability at high speeds.

End rings of traditional low speed induction machines are typically not connected to the shaft as illustrated in Figure 2-11 and the bars are used to retain the end ring [15]. This however is not a viable option at high operating speeds due to the high centrifugal forces acting on the end rings. This type of end ring can also result in rotor instability at high speeds due to non-uniform radial growth and high bending stress in the bars [37]. From this it is seen that in high speed rotors the end ring should not only be an electrical connection but also be self retaining. This can only be achieved using high strength, electrically good conducting materials. High strength aluminium alloys of the 2000 and 7000 series, with yield strengths of between 345 – 505 MPa, electrical conductivity between 20 - 35% of IACS and machinability of around 70%, can be used. High strength copper alloys include chrome copper (C18200), Beryllium copper (C17200), zirconium copper (C15000) and Glidcop®. With a yield strength of between 295 – 550 MPa, electrical conductivity of between 55 - 93% IACS and machinability of around 10 – 30 % (free-cutting brass UNS C36000 = 100%) [14] [35]. However if the end ring material’s strength is insufficient a high strength retaining sleeve shrink fitted over the end rings can be used to retain the end ring. One such material that would be perfect as a retaining ring is the MMCC Al/Al2O3 continuous fibre aluminum matrix composite. With a yield strength of more than 1200 MPa a density of 3500 kg/m^3 and modulus of elasticity of between 290-310 GPa [35].

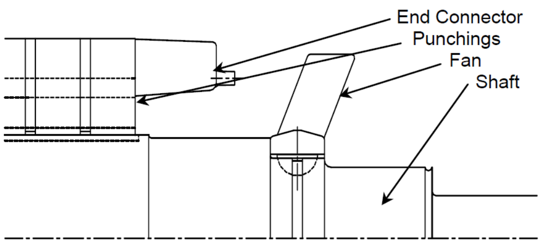

Figure 2-11Traditional IM rotor construction [15]

Conductive bars are the axial electrical flow path of the fundamental currents and can have a range of different shapes and sizes. In high speed machines the bar shape is changed to minimize stresses in the core material’s bar slots [27] [29]. The bars can also be used to clamp the lamination stack by axially pre-tensioning them [7]. The shape of the bars will depend on the manufacturing process selected. Round shaped bars can be turned on a lathe, grinded and drawn or a combination of the processes to achieve the desired diameter. The process chosen depends on the dimensional tolerance required and number of components. Drawing can also be used for shapes other than round bars. Both aluminium and copper alloys are accustomed to drawing and turning processes, however, grinding aluminium is a bit more difficult.

Connecting the individually manufactured components of the squirrel cage is crucial to ensure rotor integrity and performance. One type of end ring/conductive bar connection is welding. Types of welding processes applicable to aluminium and copper, includes laser-beam welding, brazing and diffusion bonding combined with superplastic forming.

Laser-beam welding is a fusion welding process that uses a high power laser beam as heat source. The laser-beam can be focused onto a very small area with good accuracy and is suitable for welding deep and narrow joints with very good penetration. Laser-beam welding minimizes shrinkage and distortions resulting in a strong and ductile joint. Laser-beam welding can be applied to components of thickness up to 25 mm with welding speeds ranging from 2.5m/min to 80m/min depending on the thickness. The process can be easily automated allowing high precision welding, typical applications is the laser welding of razor blades [13]. Many sources state that certain high strength aluminium alloys especially the 2000 and 7000 series is not weldable without seriously affecting the material properties. This is due to the copper percentage in the alloy which results in hot cracking [38] [39]. However aluminium 7075-T6 which is not regarded as weldable is shown to be laser-beam welded with a small reduction in strength especially after artificial aging [40].

Brazing is a joining process which uses a filler metal that is placed at the interface of the components to be joined. The temperature is raised to melt the filler metal but not the base material, this being the distinct difference between brazing and fusion welding. Filler metals used for aluminium brazing is aluminium-silicon with brazing temperature at 570-620 °C and copper alloys uses copper-phosphorus filler metal with brazing temperature at 700-925 °C. High strength connections can be obtained using brazing alloys containing silver (silver solder). The connection strength is also influenced by the joint clearance with a smaller clearance resulting in higher shear strength [13].

Joining the bars to the end rings with a welding process might affect the material properties of the base material and due to the different materials used for the core and cage, heat treatments is not an option. The result is a mechanical joining process, for instance, interference fits is investigated. This allows the cage to be assembled without using high temperature processes. Two types of interference fits are presented here namely taper and parallel fits.

The taper interference fit is obtained using a taper bar and sleeve [16], as illustrated in Figure 2-12. The force used to press the sleeve into place creates the interference fit, as the sleeve moves axially the interference is increased [17] [18]. Using this taper interference fit connection, the number of components to be manufactured will triple (two sleeves per bar). The dimensional tolerance on both components taper profile and axial length of the bar relative to the magnetic core is critical. The nature of the connection, makes it almost impossible to achieve repeatability, with the amount of interference never the same due to friction and dimensional tolerance. This type of connection also limits the size of the components and radial position of the conductive bars (bar slot cannot be positioned close to the OD of the end ring due to the sleeve).

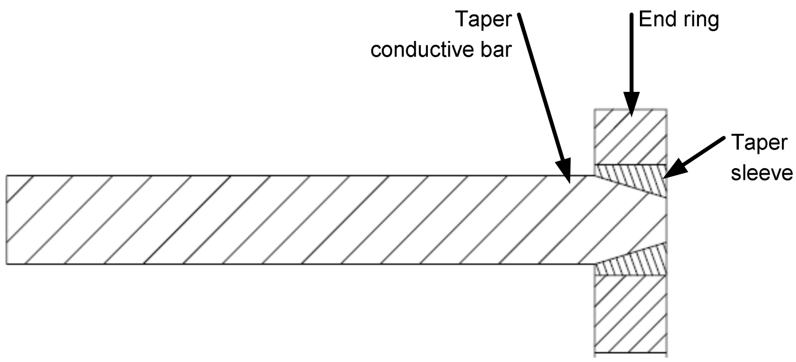

Figure 2-12: Section view of taper interference fit bar/end ring connection

Similar to the taper interference fit is the parallel interference fit, illustrated in Figure 2-13. The advantage to this connection is the fact that no extra components have to be manufactured. However, the dimensional tolerance on the bar and hole is extremely tight. For instance, using the MATLAB® program included in Appendix A, an aluminium bar (OD 10 mm) and end ring with a radial interference of 15 µm, results in a Von Mises stress of about 190 MPa at the interface. By increasing the radial interference to 20 µm, the Von Mises stress increases to 250 MPa. These preliminary calculations show that a mere 5 µm difference in radial interference increases the stress by 60 MPa. The calculations also show that the smaller the component size the greater effect.

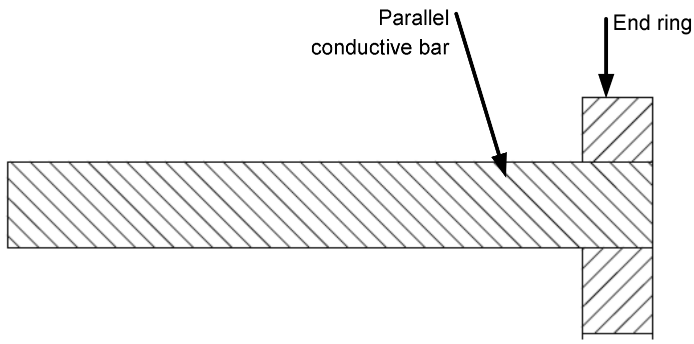

Figure 2-13: Section view of parallel interference fit bar/end ring connection

2.4 Magnetic core/shaft connection

Solid magnetic core rotors can be manufactured from a single piece of material, or to save time on machining a solid sleeve can be connected to the shaft, machined individually. This type of rotor is similar to the laminated core rotor in the sense that the magnetic core should be connected to the shaft. The core/shaft connection also has to withstand the torque transmitted at maximum speed. The following section gives detail on current design solutions and describes some of the connection types that can be used in more detail.

2.4.1 Current design solutions for the magnetic core/shaft connection

The design of M.T. Caprio, V.L. John and J.D. Herbst [9], employs an interference fit for the laminated magnetic core/shaft connection. The required interference for each component was calculated using a finite element model in Abaqus. Rotor core analysis results show a maximum Von Mises stress equivalent to 664 MPa, translating to a FOS of 1.87[1]. The assembly requires the core to be shrink fitted onto the shaft, however, due to the relative large interference, the authors express concern on conical buckling at the normalized temperature. Conical buckling analysis was done and buckling prevention measures are introduced. The laminated core is also clamped during the shrink fit process to ensure no buckling and the stiff clamping jig is removed after the assembly has cooled down.

SatCon [10] also uses a shrink fit to connect the magnetic core to the shaft, resulting in very tight dimensional tolerances (±6 µm on a 30 mm OD shaft) and a labour intensive assembly procedure. Consequently, C.P. Brown proposed a revised assembly procedure. Using the current core material (Aermet 100) and a revising the shaft material (stainless steel 410), enabled a diffusion bond to be used for the core/shaft connection. The diffusion bonding process is enhanced using a nickel alloy between the two bonding surfaces, allowing a better bond.

2.4.2 Keys or splines

Traditional low speed electric motors make use of keys or splines at the shaft/magnetic core interface [12]. The keys or splines enable the rotor to transfer the torque generated by the motor. Figure 2-14 shows two types of splines that could be used. Figure 2-14 (b) the square spline will only prevent the core from rotating relative to the shaft, where (a) the dove-tail spline will prevent rotation as well as radial outward movement.

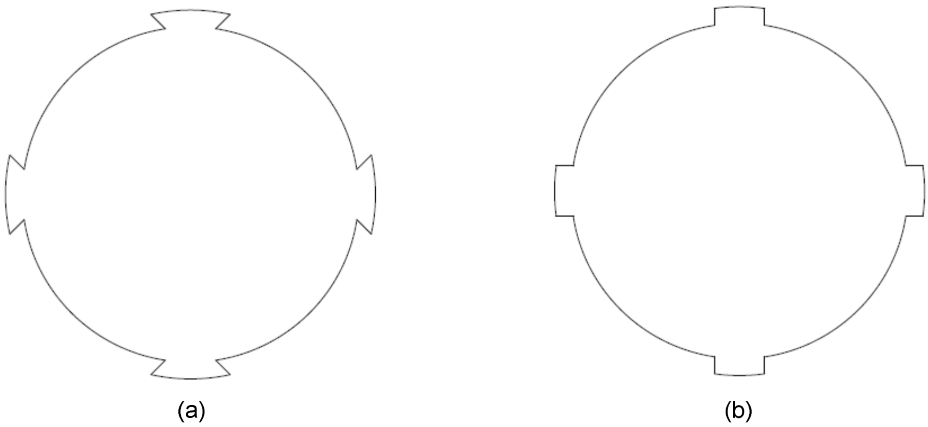

Figure 2-14: (a) Illustrates a dove-tail and (b) a square spline shaft

In high speed applications the core will have to be restricted not to rotate or move radially outwards relative to the shaft. This is mainly due to the problems a loose core can cause to the unbalance of the rotor. Therefore the square spline cannot be used for high speed applications without a secondary radial

[1] Values derived from document [**9**]

type clamp of some sort (shrink fit). Except for the balance problem at high speeds the stress in the magnetic core will also be a problem. This is due to the fact that the maximum hoop stress in a rotating ring is found at the ring's inner diameter [3] and any inconsistency in the geometry (spline) of the core's ID will cause stress concentrations. Furthermore, apart from the stress implications, the dove-tail spline profile at the core's ID will have to be wire-cut and this could rule out a laminated core as discussed in section 2.2.4.

2.4.3 Diffusion bonding

Diffusion bonding, dates back centuries and was used by goldsmiths to create "filled gold", which is a copper component covered with a thin layer of gold. The copper/gold component would be placed in a furnace and removed after a good bond between the copper and gold was formed. In the 1970's the process was refined to be used as a modern permanent bonding process. Suitable for the bonding of dissimilar metals, which includes: titanium, beryllium, zirconium, refractory metal alloys and composite materials for instance metal-matrix composites. Using a filler metal (applied by electroplating) between the bonding surfaces, will also improve the quality of the bond. The process takes place at approximately half the melting temperature of the material. Diffusion bonding is also the primary mechanism in sintering, used in power metallurgy, where a compacted powder component is heated just enough for the particles to bond (fuse) as illustrated in Figure 2-15. The bond will have the same physical and mechanical properties of the base material and when using dissimilar materials alloying takes place. The bond strength is dependent on temperature, time, pressure and the condition of the surfaces. Diffusion bonding is mainly used to fabricate complex parts at low production rates and a typical application is aircraft components. Where it is stated that a military aircraft has over 100 diffusion bonded parts [13].

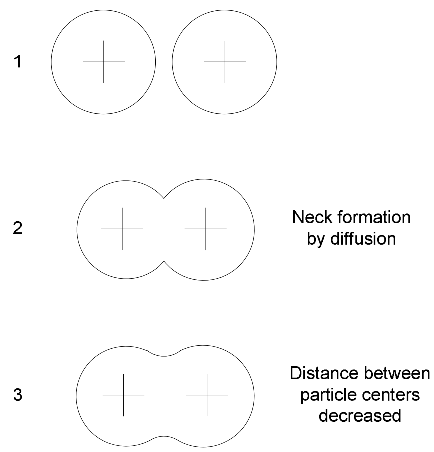

Figure 2-15: Schematic illustration of the solid-state diffusion bonding mechanism [13]

Diffusion bonding is also the proposed method of connecting the Aermet 100 magnetic core and the 410 stainless steel shaft in the revised SatCon rotor design described in [10]. The process of diffusion bonding requires pressure at the contact interface and is critical to the strength of the bond. In a shaft/hub assembly the pressure at the interface can be obtained using an interference fit. However, this will result in very tight dimensional tolerances and that is one of the problems one looks to solve with diffusion bonding. An alternative method is required and one solution is selecting the appropriate shaft material. When using a shaft material with a greater thermal expansion coefficient compared to the core material, the shaft OD will expand more in the radial direction than the core's ID during the high temperature process. Interference at the shaft/core interface will produce the required pressure. Consider the example of; a shaft OD of 79.96 mm and a core ID of 80 mm (no interference), with thermal expansion coefficients of 11.6 and 9.0 (10^{-6}/°C) respectively. With a process temperature of 800 °C the resulting contact pressure at the interface will be 85 MPa and can even be increased to ensure a strong bond.

2.4.4 Elastic shrink fits

Interference fits are non-permanent connections regularly used to connect a hub (in this case a magnetic core) to a shaft. An interference fit requires the hub component's ID to be smaller than the shaft OD, at room temperature. When using two different materials the difference in temperature at the time of measurement can influence the measured interference. Considering an aluminium disc with a radius of 100 mm a temperature difference of 10 °C will create a radial growth of 21 µm. In high precision components this could be the entire interference required.

An elastic shrink fit refers to the stress in the material due to the interference being lower than the yield strength of the material. Therefore no permanent deformation in either of the components occurs during assembly. After accurately manufacture and measurement of the components a hydraulic press can be used to force the hub into position, this is known as a "press fit". However this process can influence the amount of interference by removing material at the interface, especially if the materials have different hardness. By heating the hub or cooling the shaft and placing the hub into position a shrink fit can be utilized. After the components have returned to room temperature the interference is obtained. This process ensures no removal of material can occur and is the preferred method of assembling precision components. However, the effect of the high temperature used during assembly should be considered in terms of material properties and stress when a multi material assembly is heated (magnetic core and squirrel cage assembly).

Elastic shrink fits are used regularly to connect the laminated core to the shaft in induction machine applications [4] [10]. The stress in the hub material due to the interference required for high speed applications, limits the speed considerably. The stress in a stationary two-ring assembly can be calculated using press and shrink fit equations found in [41] [42]. Using the basic principal found in Larsonneur [3] the equations to calculate the stress in a rotating multi-ring rotor is implemented as shown in Appendix A. The analytical model was verified with FEM and practical strain gage measurements were done [43].

2.4.5 Elastic-plastic shrink fits

The main restriction of the complete elastic interference fit is that the amount of interference is critical and has a small dimensional tolerance. The dimensional limits are found from the minimum amount of interference required for high speed applications on the one hand and the maximum amount of interference limited by the yield strength of the hub material. So much so that a dimensional tolerance of ±6 µm on a 30mm OD shaft is reported by SatCon, for a purely elastic interference fit assembly [10].

Elastic-plastic shrink fit refers to the partially plasticized hub material due to a relative large interference. This is seen as a permanent connection due to the permanent change in ID of the hub component. The main benefit of an elastic-plastic fit is the dimensional tolerances of the shaft OD and the hub ID can be relaxed.

When the hub material can be stressed over the yield strength but below the ultimate tensile strength, much larger interferences can be used for shrink fits. However, the contact pressure will be less when the material is permanently deformed compared to a purely elastic interference fit and the elastic equations are no longer valid. Gamer [19] [44] [45] investigates elastic-plastic shrink fits in rotating applications and derives analytical equations for calculating the critical operating speed and interference.

2.5 Thermal effects on machine assembly

Regardless of the rotor construction and type of materials used, there will always be electrical losses in the rotor when operated under load. The losses are transformed into heat and therefore the rotor will operate at an increased temperature. The rise in temperature is dependent on the cooling and efficiency of the rotor. Although the rotor cooling is not discussed in detail in this document it can be noted that forced air cooling is implemented. In most applications the cooling of the rotor is forced airflow and the stator is cooled using a water jacket. The forced airflow is obtained by fitting a cooling fan to the rotor, similar to traditional low speed machines [10] [15]. The water jacket can be linked to a cycle, circulating a large amount of water or a reduced water supply can be used in conjunction with a heat transformer, depending on the design requirements and amount of losses [4].

Due to the different materials used for both the magnetic core and squirrel cage the rise in rotor temperature influences the design considerably. Especially if the materials used has a large difference in their thermal expansion coefficients (steel $\alpha = 12e^{-6}$ and aluminium $\alpha = 23e^{-6}$). Figure 2-16 (a) shows a section view of the magnetic core/squirrel cage assembly at room temperature and (b) shows the same assembly at an increased temperature. The illustration shows a shear force present in the rotor bars due to the relative radial growth between the end ring and core.

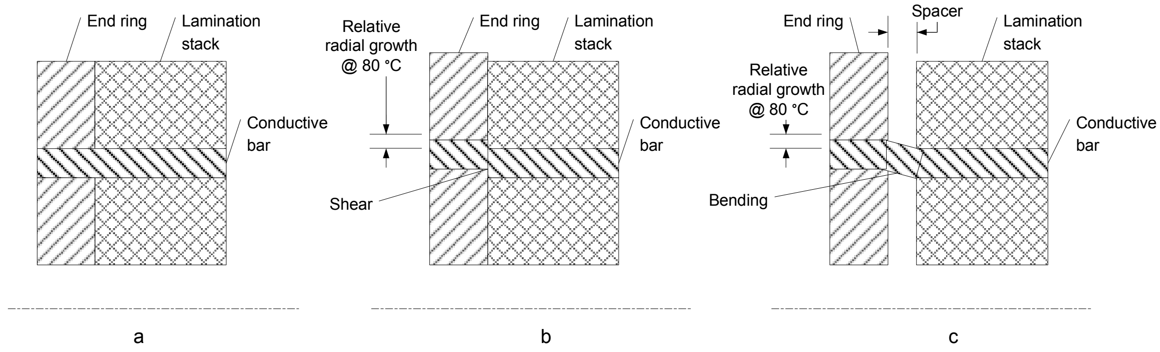

Figure 2-16: Shear and bending in the rotor bars due to elevated operating temperatures

Figure 2-16 (c) shows how this shear force can be replaced with a bending force, therefore lowering the stresses considerably. Besides the relative radial growth, some relative axial growth between the rotor bars and magnetic core can also present a problem. One solution would be to select materials with similar expansion coefficients, however, for a high efficiency rotor, this is not possible with the materials available at this moment. Other solutions are presented in the following section with regards to work done on similar design problems.

2.5.1 Current thermal effect solutions

The design of M.T. Caprio, V.L. John and J.D. Herbst [9] utilises a spacer plate as seen in Figure 2-7 the spacer has two main functions; one is to reduce the shear stresses on the bars due to the radial and axial growth as illustrated in Figure 2-17. The other is, it can be used for very fine balancing. The material selected by the designers is Inconel 718 for its high strength and low permeability. The end ring of this machine is also designed to enable deforming at high operating temperatures as seen in Figure 2-17. Allowing the end ring to deform will also reduce the stress in the bar/end ring connection due to thermal expansion.

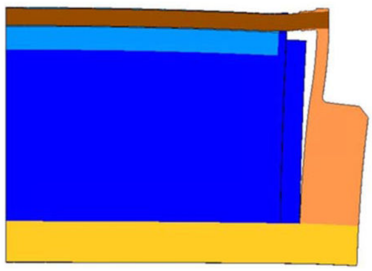

Figure 2-17: Exaggerated deformation due to temperature [9]

Another solution is utilized in L.M. Mhango's design [4], where end stops are fitted on the ouside of the end rings which restricts the axial displacement as illustrated in Figure 2-18. The electrical properties of the material used for the end stop do not realy contribute to the material selection. This is because the end stop is on the outside of the stator's core and no rotating magnetic field is directly above it to produce eddy current. Consequently the main material property required is high mechanical strength to withstand the forces due to the high speed application.

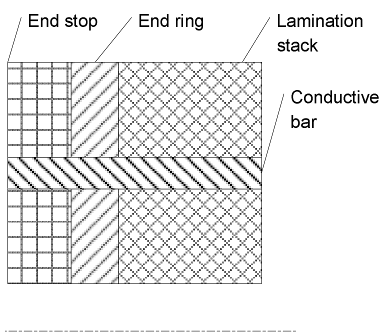

Figure 2-18: L.M. Mhango's end stop design feature [4]

The literature shows that the material stress in critical components, due to elevated temperature operation can be overcome with novel design features. Although these features complicates the design and will most likely increase the cost, it is shown as an integral part of high efficiency, high speed induction machine rotors.

2.6 Manufacturing and assembly procedures

Manufacturing in the context of this document refers to the process specified for the manufacturing of the individual components. Assembly refers to combining the individual components to form the complete product. Both these design considerations influence a design considerably. “Design for manufacture” (DFM) implies designing for ease of manufacturing individual components and “design for assembly” (DFA) implies designing for ease of assembly. Both of these considerations should be considered simultaneously; called “Design for manufacture and assembly” (DFMA). Considering both the manufacturing and assembly procedures in the concept design phase can dramatically reduce the time required to deliver a product by limiting the amount of design changes. Figure 2-19 illustrates both the conventional and DFMA design process timelines. The bar chart shows that an increased time in the conceptual design phase will ultimately reduce the time to production considerably. This is mainly due to the significant reduction in time required for the design change phase [23].

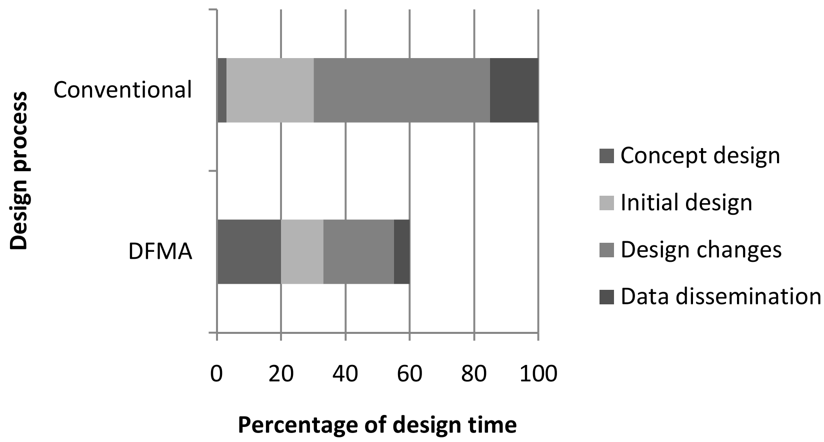

Figure 2-19: DFMA shortens the design process [23]

Apart from the huge reduction in time required for a design, the cost will also be reduced dramatically, not only due to the reduction in design man-hours, but also due to the reduction in design changes. This is due to the fact that changes to one component can have a domino effect and force changes on other components which will have a significant effect on the time and money required especially later in the design process.

DFMA is an intricate part of competitive development and can be best utilized using software packages specially developed for DFMA [28]. With the addition of finite element model (FEM) simulation packages, for instance SolidWorks® Simulation, the design can easily be manipulated to compare different design scenarios and optimize components. These two optimization software packages can greatly enhance an engineer's designing ability and reduce changes later in the design process. In order to include DFMA in the development of a product, the design process should look similar to Figure 2-20. After the concept design a DFA analysis is conducted in order to simplify the product, followed by a DFM analysis which includes cost estimation. The best concept design is selected, followed by material and manufacturing process selection, after which a detailed DFM analysis is conducted and the product is put in production.

DFMA will be an intricate part of the induction machine rotor mechanical design, due to the complexity of the components and restrictions on materials that can be used. Throughout Chapter 2 all the mechanical design considerations discussed included manufacturing and assembly considerations showing the integral nature of DFMA in each rotor component. The implementation of DFMA will become apparent during the mechanical design presented in Chapter 3 and the manufacturing and assembly procedures discussed in Chapter 4.

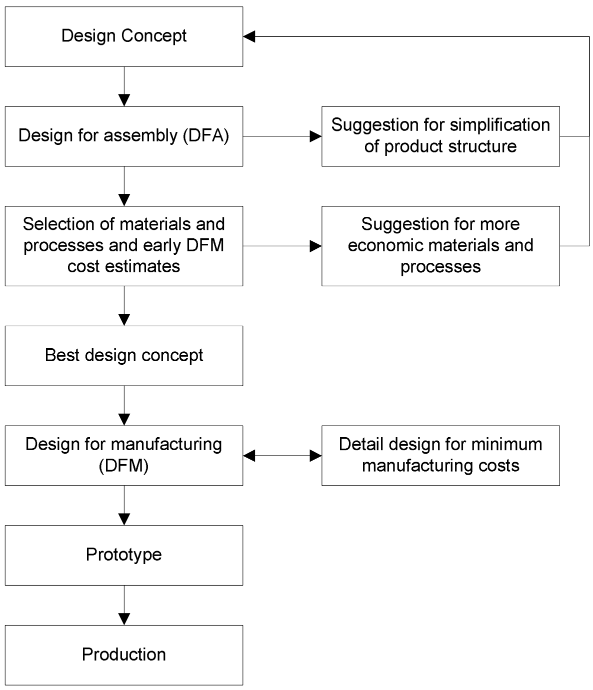

Figure 2-20: Typical DFMA procedure used by DFMA software [23]

2.6.1 Manufacturing processes

In this section the proposed manufacturing processes mentioned in the chapter will be briefly discussed in terms of capability, production rate and cost. The discussion will include die casting, milling, turning, wire electric discharge machining (EDM), grinding, laser cutting, hot isostatic pressing (HIP) and cold isostatic pressing (CIP);

Die casting also known as "pressure-die casting" is characterised as a permanent-mold casting method, typically used for casting engine blocks, tools and toys to name but a few applications. Some common materials used include; aluminium, magnesium, zirconium, copper and their alloys. Component size and weight vary and can be anything from 10 g to 50 kg. With a surface roughness of between 1 to 2 μm compared to sand casting's 5 to 25 μm roughness. The shape complexity is also good with a 3 to 4 rating[2] relative to sand casting which has a 1 to 2 rating. Dimensional accuracy of die casting is rated as the best, compared to sand, shell, plaster and centrifugal casting with a typical dimensional tolerance of ±0.001 to 0.005 mm/mm and allows for a sectional thickness of between 0.5 to 12 mm. However, it is stated that a minimum of 10,000 units have to be produced before the production is viable compared to sand castings, which requires only one unit. This is mainly due to cost implications and although the process can be automated and labour is relatively low the initial cost of the equipment and service and replacement of the dies are relatively expensive. During the die casing process the molten metal is forced into a die to create the required shape at pressures ranging from 0.7 to 700 MPa. Two types of die casting machines are typically used namely; hot and cold-chamber. Cold-chamber casting is normally the preferred casting method for aluminium and copper alloys. The cold-chamber refers to the molten metal being poured into the injection cylinder which is not heated the cylinder can be positioned horizontal or vertical depending on the application [13].

HIP and CIP is associated with powder metallurgy and is used to enhance uniform density through hydrostatic pressure in green compacts[3]. The CIP process is based on the metal powder being placed in a rubber mold and hydrostatically pressurized in a chamber, using water with pressures as high as 1000 MPa. This process can produce components, more complex than components produced through HIP, however, HIP can produce components larger in size. In HIP the metal powder mold is usually made of high-melting point sheet steel. The pressure in the vessel is about 100 MPa, however, it can be as high as 300 MPa. Instead of water as in the case of CIP, a high temperature inert gas is used to pressurize the green compact at temperatures up to 1200 °C. HIP can produce compacts having almost 100% density and good mechanical properties. Therefore the process is mainly used to produce super alloy components as well as improve the properties of super alloy casting, mainly for the aerospace industry [13].

Turning is a process based on the part turning while being formed using a cutting tool on a lathe or a similar machine. These types of machines are extremely versatile and capable of producing a wide range of components in different shapes and sizes, however, it is mainly used to produce round parts (shafts, pins, sleeves). The cutting tools used are different for each workpiece material group and required application (outside turning, boring and parting), the cutting tools are unique in terms of material, shape and size. The cutting speed at which material is removed (material-removal rate) is also different for each workpiece material group. All the cutting tools optimum shape and material-removal rates were largely found through experience and is documented extensively. The dimensional tolerance and surface finish obtained through turning is dependent on numerous factors including; material-removal rate, workpiece material and stiffness of the workpiece and cutting tool to name but a few. The cutting parameters can be changed to optimise the process, depending on the application, and will result in a change in cost and production rates [13].

[2] Relative rating with 1 being the worst and 5 the best
[3] Metal powder pressed into the desired shape

Milling is a machining process where a rotating cutter removes material and can be moved along various axes, with the amount of axes dependant on the milling machines capability[4]. This material removal process can be used to produce a range of components including complex shapes, producing anything from simple plates with holes to complex turbine fins and worm gears. The complex shaped parts are made possible through CNC milling machines and the wide range of cutting tools available. As in the case of turning, the material-removal rates as well as cutting tool shape and material, was found through experience and is well documented. During the design of a component it is imperative that the clamping of the component is considered. The dimensional tolerance is dependent on the milling machine itself, clamping as well as size of the component [13].

EDM wire cutting is based on the erosion of material through spark discharge. The metal component is placed in a dielectric fluid, while wire made of brass, tungsten, copper or molybdenum is moved along the desired profile. Wire EDM is similar to a band saw and as the wire approach the workpiece a spark will result as soon as the potential difference between wire and workpiece is sufficiently high, consequently removing a small amount of material. This process is repeated continuously and the profile is machined at a voltage of between 50 to 380 V and the current dependent on the material removal rate required. The surface finish is dependent on the material removal rate and wire thickness, for roughing cuts a typical diameter would be 0.3 mm and for a finishing cut the diameter would be 0.2 mm. The main advantage of wire EDM is the process ability to manufacture components with a large length to width ratio, for instance a long sleeve. The other advantage is that the manufacturing process is capable of producing intricate profiles. However, the process is time consuming and therefore very expensive. The clamping of the component is also limited and should be considered during the design [13].

Grinding is a finishing process which is used to manufacture components of high dimensional accuracy and fine surface finishes. The process also allows for the machining of very hard and brittle materials and the abrasive wheel can be dressed into a desired shape, allowing intricate designs. However, the process is limited to very small cuts[5], mainly due to the affects a rise in temperature might have on the surface properties of the workpiece. The rise in temperature is dependent on the wheel diameter, wheel speed, workpiece speed and depth of cut, with the depth of cut having the biggest influence. Some of the temperature affects include; Tempering and softening of the workpiece surface, burning which is characterized by a bluish colour of the surface, heat checking and residual stresses. Residual stresses can also influence the dimensional accuracy of the workpiece and can be reduced by lowering the wheel speed and increasing the workpiece speed, the use of softer-grade wheels will also reduce the affects. Due to the relative small material removal rate and cost of grinding wheels, the process is expensive and is only used if the dimensional tolerance, surface finish or material properties impose it [13].

In conclusion, the selected manufacturing process will depend on the component's geometry, material properties, dimensional accuracy and surface finish required. The number of components to be produced is also a critical factor and will influence the decision of casting process, special jigs and pre-

[4] Up to 5 axes including; rotating cutter's x, y and z and component rotation

[5] Amount of material removed preferably ≤ 0.5 mm for a 30mm OD shaft

formed cutting tools will be used. Independent of the machining process selected, some design considerations that will affect the design includes;

- Selecting an appropriate manufacturing process for a specific design will depend on the component's shape, dimensional tolerance and surface roughness required. Figure 2-22 illustrates typical surface roughness obtain using different forming processes, the dimensional accuracy is also directly proportional to the roughness obtained.
- Clamping of the workpiece should be considered and thin parts might have to have excess material or special clamping jigs to allow rigid clamping.
- Each component's dimensional tolerance and surface finish should be as wide as possible, without affecting the performance of the component. The increase in time required for a specific machining process to obtain the required surface roughness is illustrated in Figure 2-21.
- High precision components shouldn't have holes, keyways or inclusions which might cause chatter and influence the dimensional accuracy.
- Shoulder radii should be as large as possible and the use of special cutting tools should be minimized.
- Material selection should consider machinability to ensure ease of manufacturing.
- Stiffness of the workpiece should be considered when dimensional accuracy and surface finish are important, in order to minimize chatter and workpiece deflection.
- In all manufacturing processes it is critical to have the blank as close as possible to final dimension to reduce the amount of material to be removed, consequently reducing manufacturing cost [13].

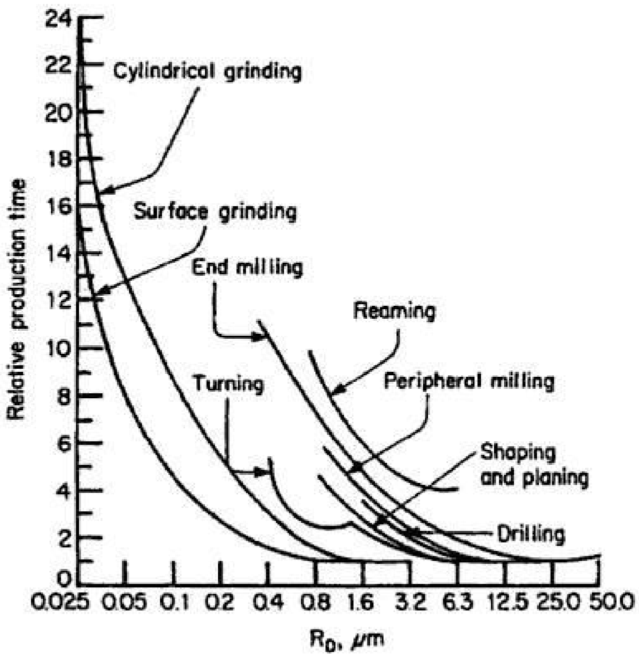

Figure 2-21: Comparing time required to obtain a specific surface roughness using different manufacturing processes [46]

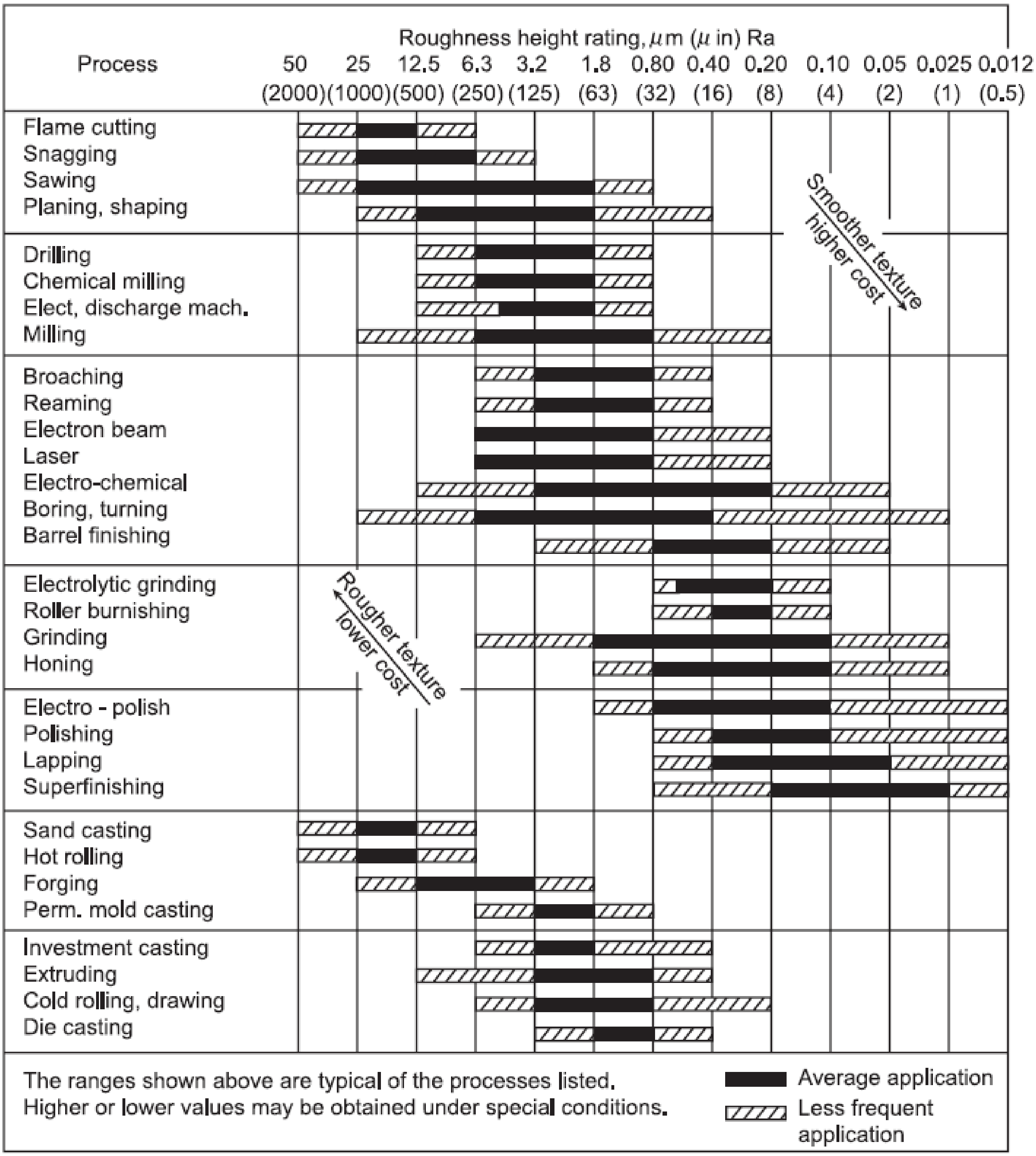

Figure 2-22: Typical surface roughness for specific manufacturing processes [47]

2.7 Critical overview

As illustrated throughout the chapter, the development of a high speed induction machine rotor involves an intricate and iterative design process that considers both mechanical and electrical parameters. The purpose of this section is to critically evaluate the proposed mechanical design solutions found in the literature, in the context of the problem statement of the dissertation.

It is apparent that the laminated cage rotor is the preferred rotor configuration in terms of efficiency and should be used whenever the operating speed allows it [2] [24]. The maximum operating speed for a laminated cage rotor is more often than not determined by the lamination material strength [10]. Commonly used low strength Silicon-iron alloy is not always suited for high speed applications. High strength Cobalt-iron alloys as well as custom manufactured lamination material can be considered [31] [32]. The cost implication however, should be weighed against the loss in efficiency when using a solid coated or cage rotor.

The squirrel cage is shown as the preferred low resistive electrical flow path and both high strength aluminium and copper alloys can be used in high speed applications [9] [11] [15]. The manufacturing of the squirrel cage is influenced by the magnetic core material. If heat treated lamination material is used for the magnetic core, casting of the squirrel cage is eliminated. The low strength of, as-casted, materials is also a critical limitation. Furthermore, if the low strength and high temperature problems can be overcome, the casting process can only be considered if a large number of rotors are produced [13].

Due to the fact that only one rotor will be produced during the development, the only viable option is to manufacture each component of the squirrel cage individually and then assemble it into the core.

Four types of connections are described for the core/shaft connection, however, not all of the connections discussed are viable options for a laminated core. The literature shows that the connection type is critical and contributes significantly to the material stress in the rotor [3] [19]. It is also essential that a contact pressure is present, at the core/shaft interface, throughout the operating range, for both rotor stability and to transfer the produced torque [9].

Table 2-2 summarises some design parameters of high speed induction rotors found in the literature. The table shows the rotor's power, dimensions, magnetic core type, core/shaft connection, materials selected and squirrel cage assembly method.

The literature summarised in Table 2-2 illustrates some typical solutions for the design considerations encountered in the mechanical design of an induction machine rotor section. Furthermore the summary also clearly indicates some preferred solutions for specific considerations. For instance for the shaft/magnetic core connection, four out of the five designs use shrink fits as the connection method. Furthermore all five designs use a copper alloy as the squirrel cage material allowing an end ring/conductive bar, brazed connection. Table 2-2 also shows that laminated core rotor with a designed surface speed of 286 m/s is practical, however, the maximum speed is greatly influenced by the lamination material used.

Table 2-2: Summary of current high speed IM design solutions

Reference	[10]	[10][6]	[9]	[7]	[4]
Power (kW)	Unknown	Unknown	2000	21	100
Speed (r/min)	60,000	60,000	15,000	50,000	27,000
OD (mm)	110	110	364	50	123
Surface speed (m/s)	345.58	345.58	285.88	130.90	173.89
Rotor type	Solid cage	Solid cage	Laminated cage	Laminated cage	Laminated cage
Shaft/core connection	Shrink fit	Diffusion bond	Shrink fit	Shrink fit	Shrink fit
Core material	Aermet 100	Aermet 100	AISI 4130 laminations	Silicon steel laminations	Unknown lamination
End ring material	Glidcop®	Glidcop®	UNS C17510	Glidcop®AL-60	Cu alloy
Bar material	Glidcop®	Glidcop®	UNS C15000	Glidcop®AL-15	Cu alloy
Bar/end ring connection	Braze	Diffusion bond	Braze	Braze	Braze
Shaft material	AISI 4340	SS 410	AISI 4142 (Q&T)	Unknown	Unknown

2.8 Initial induction machine rotor design decisions

The literature clearly indicates preferred solutions for some of the IM rotor section design considerations. These preferences, facilitated initial design decisions made by the McTronX research group in order to deliver the design solution in the required time frame.

The McTronX research group indicated that a laminated cage rotor will be the selected rotor design for this project. A laminated core will be used even if the mechanical properties of the lamination material available, forces a change in the design specification. The core/shaft connection is also selected and a shrink fit is to be used. Some geometry constraints have also been introduced due to the preliminary electromagnetic design of the stator and initial rotor dynamic analysis. The initial design decisions as indicated above will be the starting point of the detail design discussed in Chapter 3.

[6] Design has not been implemented. It is only a proposed design by the author.