Squirrel-Cage Rotor for AC Induction Motors

A.H. Bonnett, T. Albers, Squirrel-Cage Rotor Options for AC Induction Motors, IEEE Trans. Industry Applications, 37(4), 1197-1209, 2001

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Introduction

유도전동기의 일반적 특징 :

- **work-horse of modern industry**
- 튼튼하고 가격이 저렴하여 산업계에 가장 널리 사용
- 고정자, 회전자, 베어링으로 구성
- 고정자권선의 교류전류는 전원에서 직접 공급
- 회전자 권선에서는 고정자 교류전압의 유도작용에 의해 교류전류가 인가

유도전동기의 사용 구분

단상 유도전동기 (~ 1 hp, 소형)	선풍기, 청소기, 에어컨, 주스 믹서, 세탁기, 냉장고 등의 가정용품
3상 유도전동기 (대형, 수십~수백 hp)	펌프(pump), 휀(fan), 압축기(compressor), 제지기(paper mill), 방직기(textile mill) 등 산업용

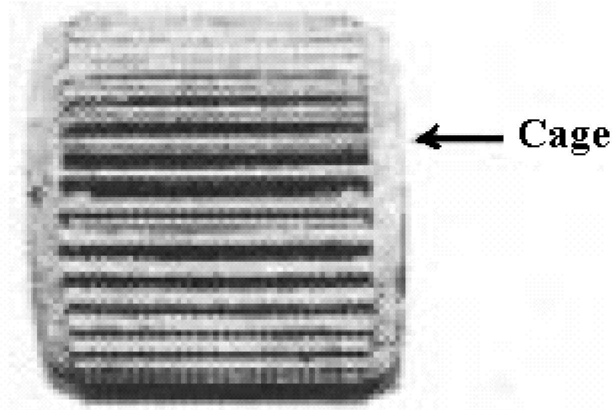
Introduction

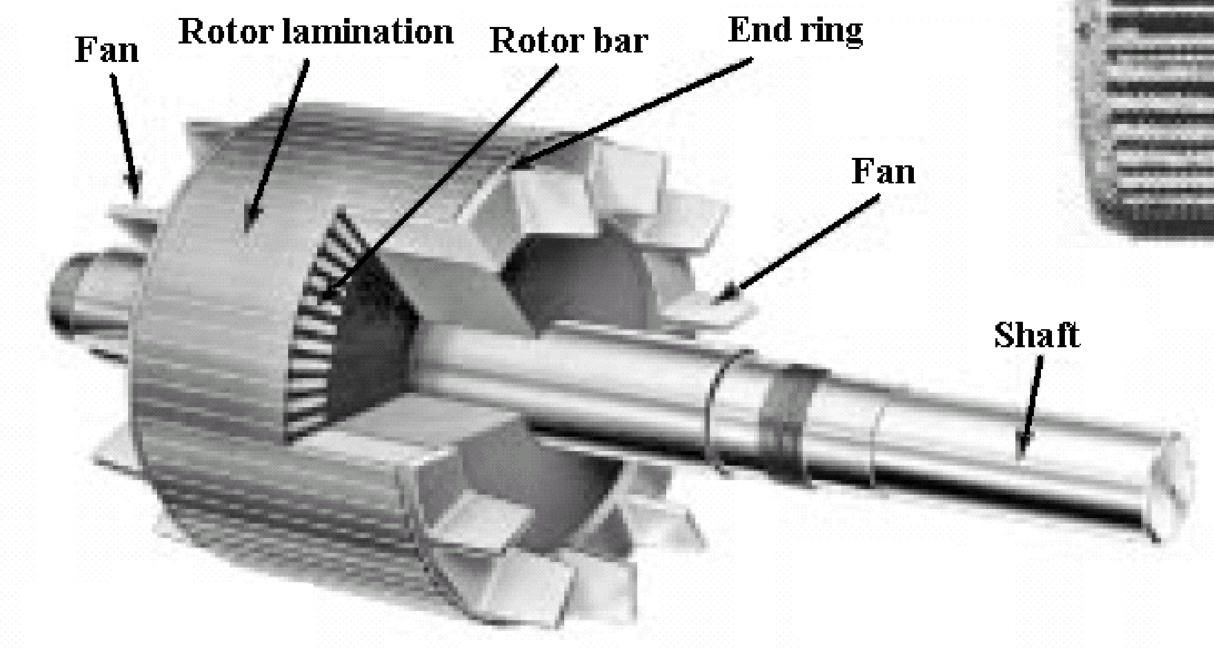
유도전동기의 구조적 특징 :

- 3상 권선이 회전자 frame 내부 표면 위에 있는 슬롯 속에 설치
- 고정자 철심은 성층된 강자성체를 사용, 철심 표면에는 슬롯이 절단
- 회전자 권선 형식: 농형(squirrel-cage type), 권선형(wound-rotor type)
- 농형 권선은 회전자 슬롯 속에 삽입된 알루미늄 또는 동봉(copper bar)로 구성되며, 양측 끝부분은 단락됨
- 권선형 회전자 권선은 고정자 권선과 같은 형태, 회전자 권선의 끝 부분은 3개 slip ring과 연결. 고정 브러시를 슬립 링에 접촉하면 회전자 권선은 외부 회로와 연결

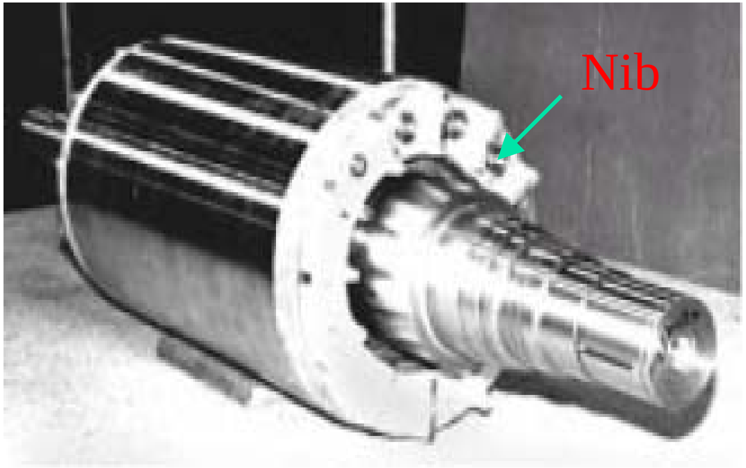
Rotor construction

Rotor components: shaft, end ring, fan, rotor bar, lamination (air ducts, nibs).

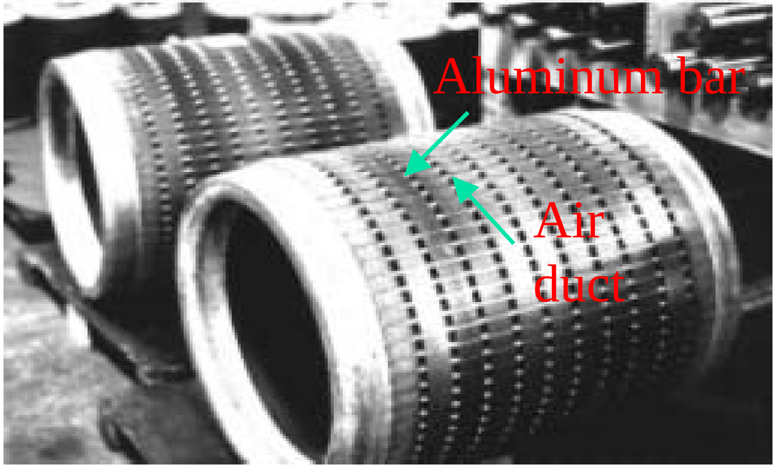




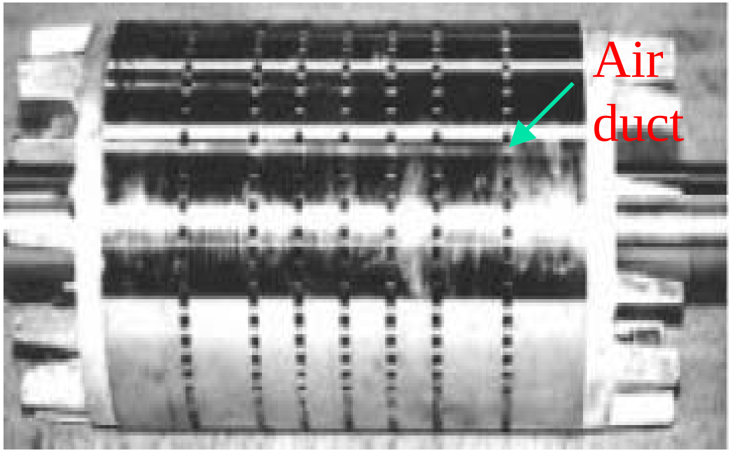
Typical cast rotor assembly



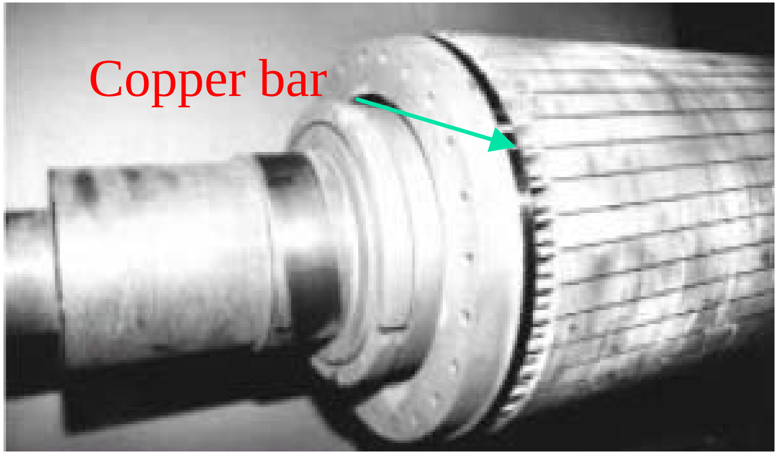
Typical cast aluminum rotor assembly



A large slow-speed fabricated aluminum bar rotor with air ducts



Typical cast aluminum rotor assembly with air ducts



A large high-speed fabricated copper bar rotor

Rotor components

Name	Function	Material	Others
Lamination	■ Carry the magnetic flux ■ Transfer heat ■ Provide structure for the cage	■ Carbon or silicon steel	
Rotor shaft	■ Be provided to position the rotor to the load ■ Be facilitated by the bearings	■ High-strength 1045 steel CR-MO1442, Stainless 416, Carbon 1144	
Fan	■ Provide air flow to cool the motor		
Air ducts			
Nibs	■ Balance the rotor		

Rotor shafts configuration

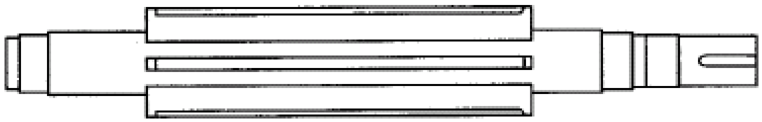
- 회전자 축 재료는 통상 고강도 등급의 1045 steel을 사용
- 특수한 경우, Cr-Mo 1442, Stainless 416, Carbon 1144

The rotor shaft must be carefully sized

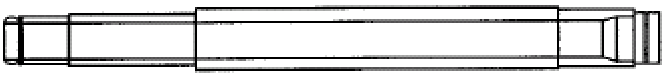
- **to transmit the torque to the load**
- **to carry torque due to momentary transients.**

The shaft size must also be

- **large enough that the rotor does not deflect and rub the stator during startup or running.**



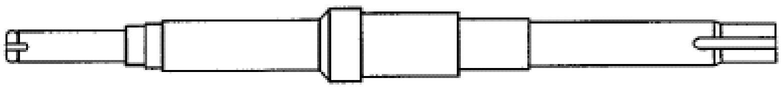
Large Motor Spider Shaft



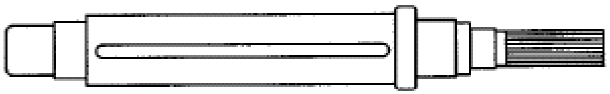
Vertical Motor Hollow Shaft for Pumps

Totally Enclosed Fan Cooled Shaft

Open Dripproof



Close-Coupled Shaft for Pumps



Splined or Geared Take-off Shaft

Rotor forces

- 농형 회전자는 전원과 직접 연결되지 않고, 고정자권선에 의해 생기는 자속(flux)으로부터 유도에 의해 동력이 얻어짐
- 공극 자속(air-gap flux)은 정현적으로 분포되고 회전자에 대해 회전하는 것으로 가정
- 기전력(electromotive force: EMF)은 각 회전자 봉에서 유기되고, 크기는 회전자 봉을 끊는 자속 밀도의 양과 비율에 의해 결정
- 통상의 슬립에서 봉 전류는 유기되는 EMF와 거의 동위상이고 정현파
- 각 봉 내의 전류는 토크를 발생하는 봉에 힘으로 작용
- 토크는 고정자 권선의 동기속도보다 작은 속도로 회전을 일으킴
- 슬립(slip) : 동기속도와 회전자 속도 사이의 속도차

$$\text{slip } (\%) = (N_s - N_r)/N_s \times 100$$

여기서 N_s :동기속도(synchronous speed), N_r : 회전자 속도, f_r: 회전자주파수

$$N_s = (120 \times \text{line frequency})/\text{poles (rpm)}$$

$$f_r = (\text{slip} \times \text{line frequency})/\ 100 \text{ (Hz)}$$

Rotor forces

- 기동시 회전자 권선 내 전류의 주파수는 전원주파수(0 속도)에서 슬립주파수 (동기속도에서)까지 변화
- 이 전류에 대응하는 힘이 회전자주파수에서 반경방향으로 봉을 변위시킴

- 회전자 고장의 주요 원인은 회전자에 작용하는 다음과 같은 여러 응력 (stress)의 결합에 의해 발생
- 열 응력(thermal stress)
- 전자기력 응력(electromagnetic stress)
- 잔류 응력(residual stress)
- 동적 응력(dynamic stress)
- 환경적 응력(environmental stress)
- 기계적 응력(mechanical stress)

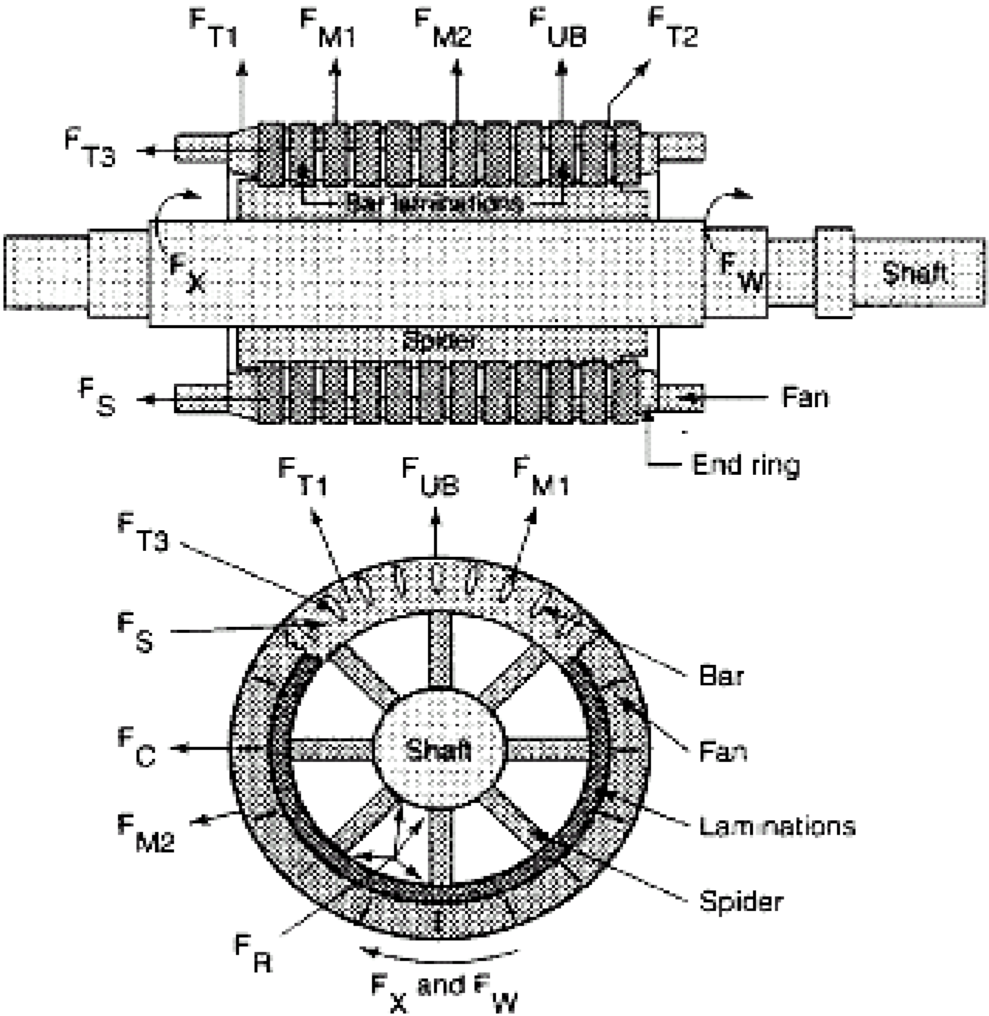
- 전동기가 적절하게 설계, 제작, 조립, 설치, 운전 및 보수유지 된다면, 이들 응력은 허용치 이하로 유지가능하고, 오랫동안 기능 유지 가능

Motors stress

Stator stresses

Thermal stresses	Residual stresses	Mechanical stresses
• Thermal aging • Voltage variation • Cycling • Loading • Ventilation • Ambient	• Stress concentrations • Uneven bar stress	• Casting variations • Loose laminations • Incorrect shaft/core fit • Fatigue or part breakage • Poor rotor to stator geometry • Material deviations
Magnetic stresses	**Dynamic stresses**	**Other stresses**
• Rotor pullover • Noise • Vibration • Off magnetic center • Saturation of lamination • Circulating currents	• Vibration • Rotor rub • Over-speeding • Cyclic stresses • Centrifugal force	• Misapplications • Poor design practices • Manufacturing variation • Loose bars, core • Transient torques • Wrong direction of rotation
	Environmental stresses	
	• Contamination, Abrasion • Foreign particles • Restricted ventilation • Excessive ambient temp	

Rotor forces



F_W : working torque

F_{UB} : unbalance dynamic force

F_X : tensional vibration and transient torques

F_R : residual forces from casting, welding, machining & fits (radial, axial and other)

F_{M1} : magnetic force by slot leakage, flux, vibration at 2X freq. of rotor current

F_{M2} : magnetic force by air-gap eccentricity

F_C : centrifugal force

F_{T1} : thermal stress by end-ring heating

F_{T2} : thermal stress caused by temp change in bar during start (skin effect)

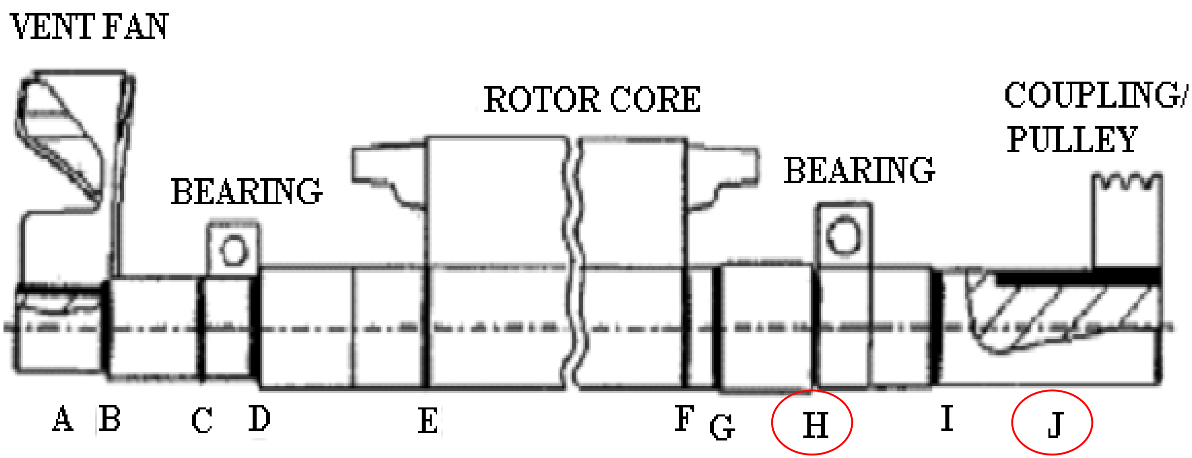
F_{T3} : thermal stress by axial bar growth

F_S : axial forces by skewing the rotor bar

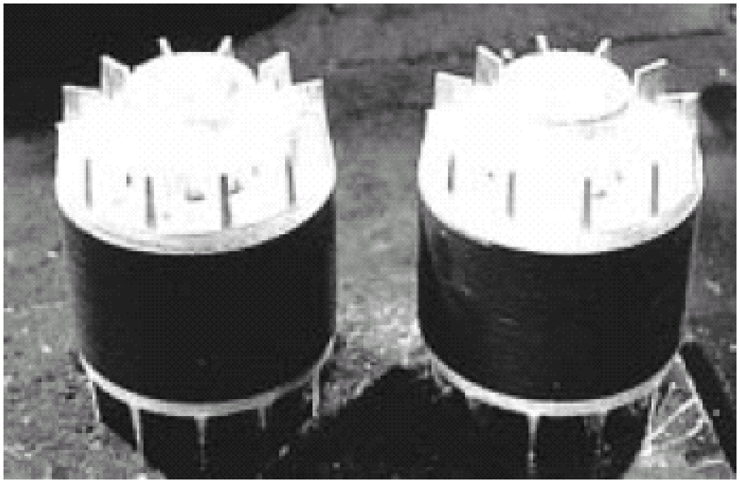
W : rotor weight

Rotor design stress concentration

- 설계 응력집중이 발생하기 쉬운 축 변단면을 표시
- 표면 불연속 위치: bearing shoulder, snap ring groove, keyway, shaft thread, hole
- 축 손상, 부식(corrosion)
- 피로 크랙, 고장은 통상 이 부분에서 발생
- 전동기의 가장 일반적 위치: 베어링저널의 shoulder(H), coupling keyway(J)
- 대부분의 베어링 고장은 축방향 하중(axial load)의 결과



Construction of cast rotors



Die-cast rotors before the casting gates are removed

Three basic methods of cast rotors

Centrifugal casting	Excellent quality	The amount of aluminum is limited. Also long narrow rotor slot sections must be avoid.
High-pressure die casting	Excellent quality	
Low-pressure die casting	Excellent rotor	Larger rotor can be cast, also long narrow slot can be cast.

Molten aluminum or an alloy (approximately 1550 F) be injected into a preheated stacked rotor core. Mold are used to form the end rings, the fan blades and the balance nibs.

Cast rotors are frequently heat treated after casting to reduce surface loss. For one such process, after the rotor is turned to size, the rotors are heated to about 900 F, then rapidly cooled by water quenching. The major effects of flame treatment:

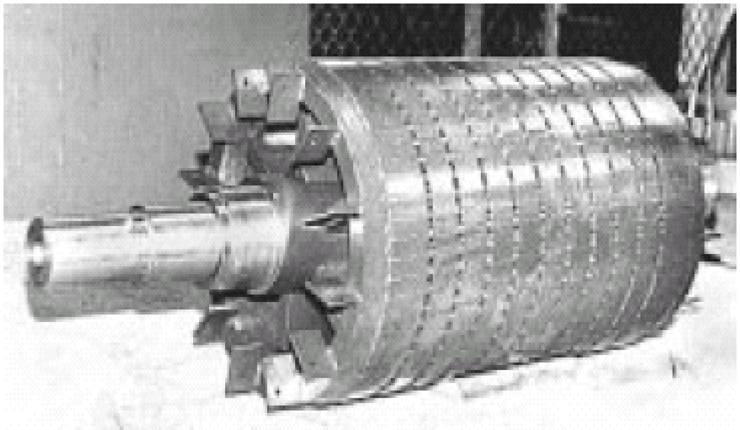
- Smear on the rotor surface is removed. This smear is caused by the cutting tool when the rotor outside diameter is finished. The smear shorts laminations together And cause inter-laminar currents.

- The thermal shock caused by rapid water quenching of the heated rotor tends to separate the bars and lamination, breaking up shorts between bars and laminations which were missed by the core plating process.

- The heat promotes oxidation of the bar surface. The aluminum oxide coating thus formed on the bar adds to the insulation between the bar and lamination.

The effectiveness of flame treatment depends on the temperature, the rate of temperature rise, and type of gas used for the flame propagation.

Construction of fabricated rotors



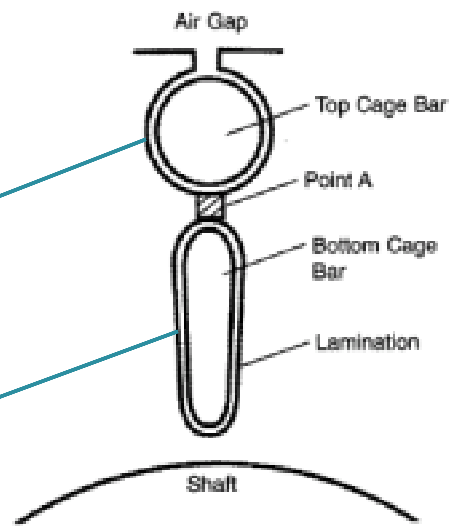
Typical fabricated rotor with air ducts

Rotor bars are individually inserted and then shorted together one each end rings.

Traditionally, fabricated rotors are made using copper or copper alloy rotor bars and end rings

The top cage is usually a high-resistance alloy to produce high starting torque

The bottom cage is low-resistance copper to produce low running loss



Double-cage fabricated rotor cross-sectional view

Bar shape

The shape of rotor bar has a lot to do with the performance of the motor, Especially during acceleration.

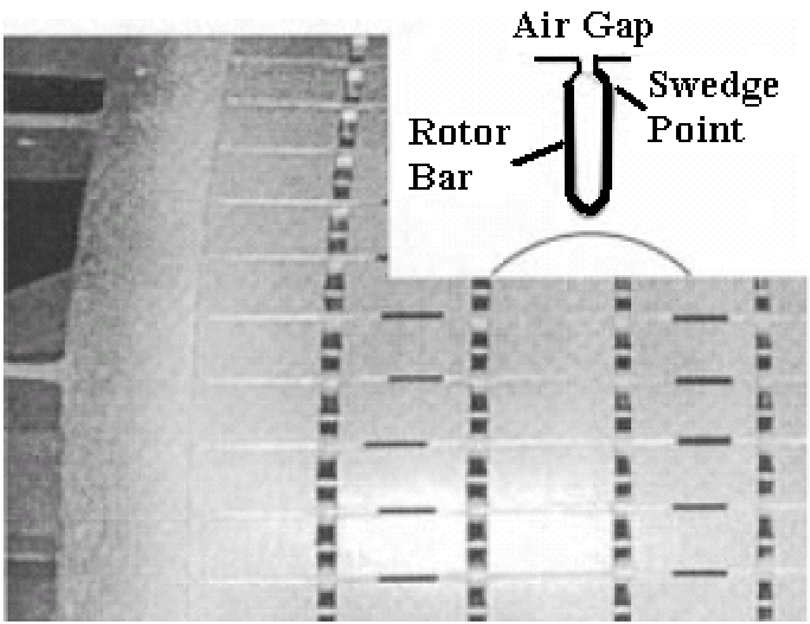
A variety of possible rotor bar shapes

There is a phenomena known as “skin effect” which causes rotor bar current to crowd to the top of the bar during starting.

This feature can be used by the designer to establish the required starting torque and starting current.

As the motor comes up to speed, current flows through an increasing proportion of the bar, until at full speed the entire bar is carrying current equally.

The slot shape also determines the extent to which the lamination steel can be utilized.



Cast rotor	Give peak performance characteristics, provided section of the slot are not too narrow to cast.
Fabricated rotor	Provide both mechanical and electrical properties.

Tape shape slot	Be loaded to maximum magnetic flux density for the full length of the tooth.
Rectangular slot	Permit maximum magnetic densities only at the bottom part of the tooth.

The tapered bar used on four-pole and slower rotors is easily extruded shape with Tight dimensional tolerances, and drives easily into a skewed rotor.

The wedge bar used on two poles is also an easily extruded shape to tight tolerance And the shape minimizes any bar movement due to looseness, centrifugal force.

Rotor bar material

- The two most common rotor bar material are copper and aluminum.
- Traditionally, cast rotors have been aluminum and fabricated rotors have been aluminum or copper.
- Aluminum alloys and copper alloys have been available for special purpose.
- Recently, a number of manufactures have change from copper to aluminum.

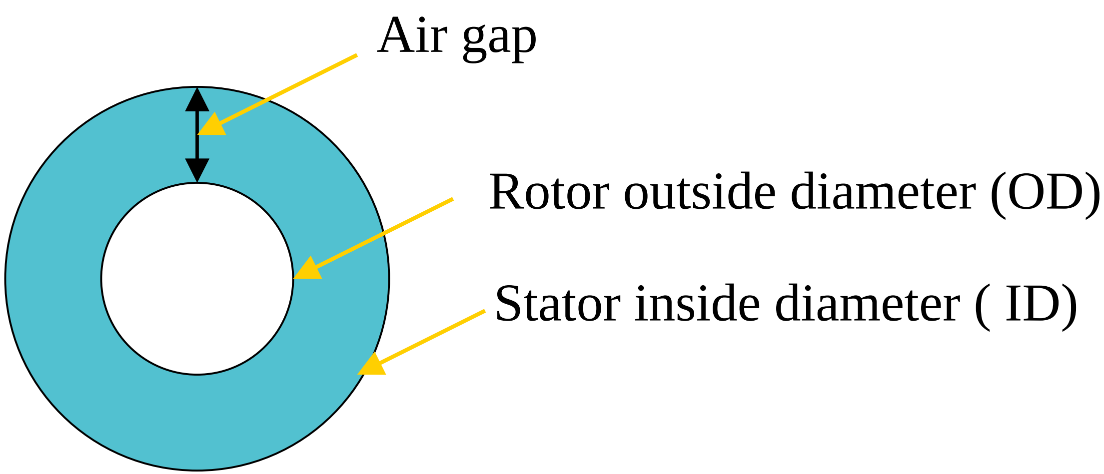
Aluminum holds several advantages over copper, the most obvious of which is cost. Not only is aluminum cheaper by the pound than copper, but a given motor will use Fewer pounds of aluminum than copper.

When rebaring a rotor, care must be taken to determine the bar and end ring Conductivity so that the proper speed-torque characteristics can be maintained.

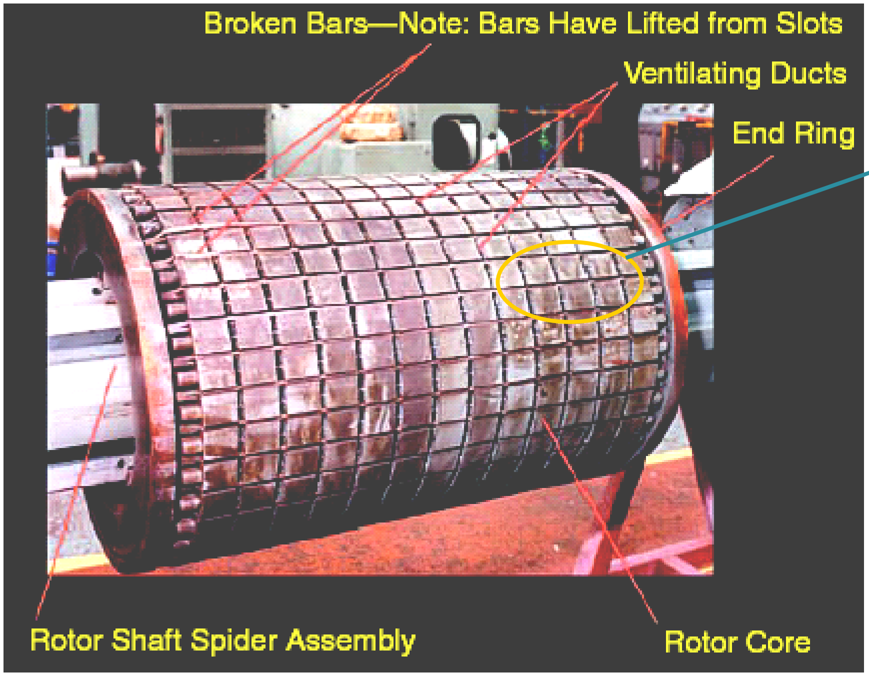
Air-gap

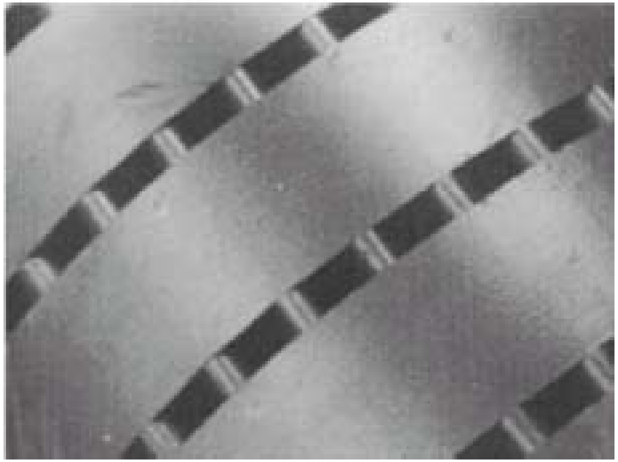
- The size of the air gap influence some of the operating characteristics of the motor.

- The longer the air gap, the greater the magnetizing force necessary to establish the magnetic field. More magnetizing current means a lower power factor. Thus for the best power factor, it is better to keep the air gap small



Air ducts

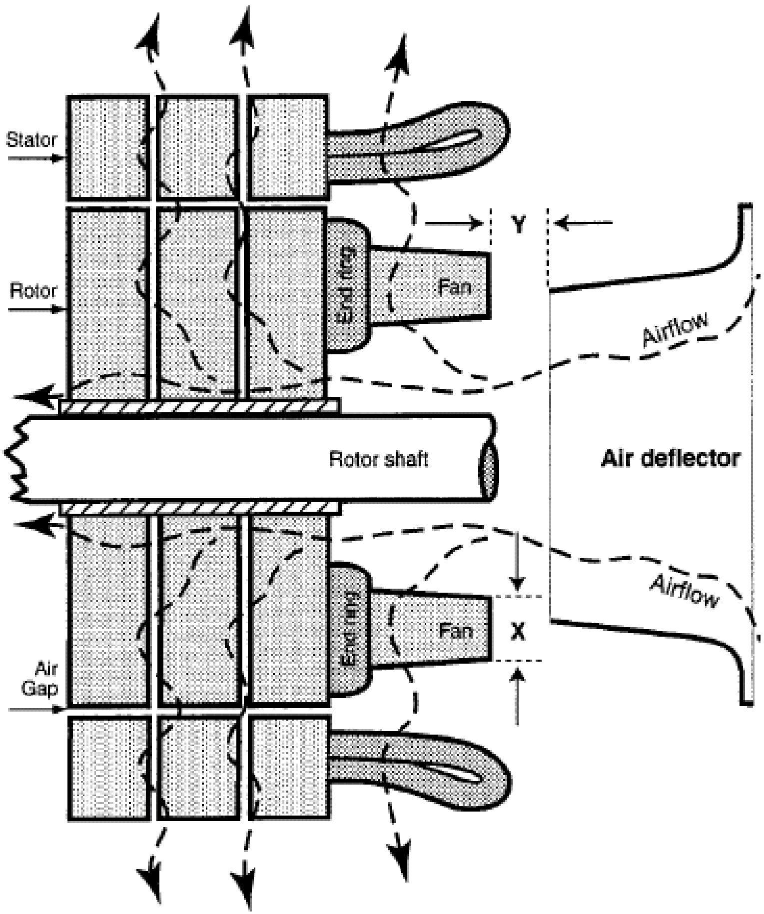




Usually, on large open drip proof motors (about 200 hp), it is necessary to cool the Rotor by the use of air ducts which allow air to travel down the shaft spiders and exit Through the air ducts of the rotor in the stator.

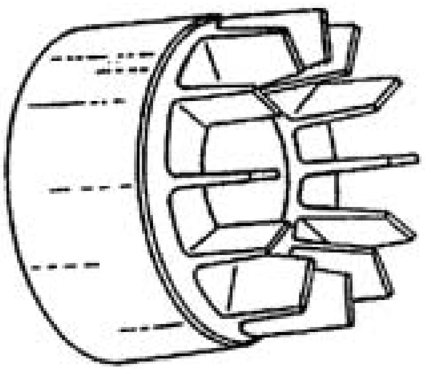
Cooling fans

Rotor fans are used to transfer the heat out of the rotor bar and stator slot. Without them, It could increased winding temperature 5° – 7° C.

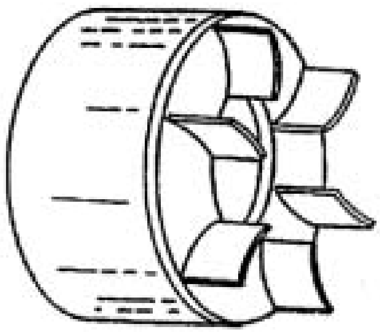


Some are cast as a part of the rotor end ring, while others are separate parts fastened to the shaft.

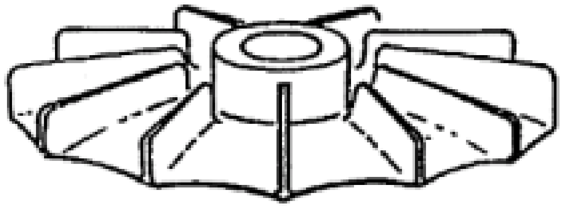
Sometimes on fabricated rotor copper designs, the bars are extended to the shaft to form fan blades.



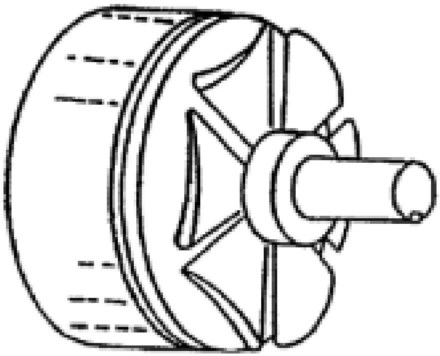
Standard radial fan



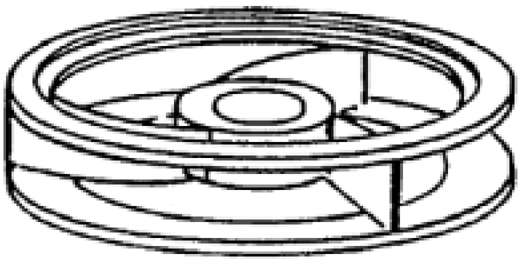
Unidirectional back-sloped fan
(4-6 dB noise reduction)



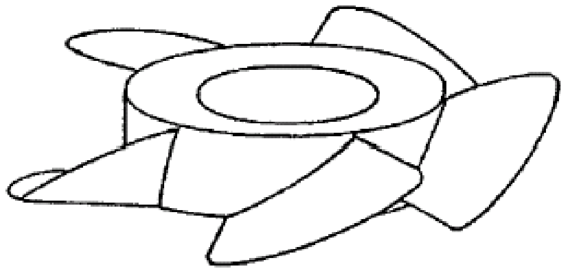
Radial fan
(high efficiency, high pressure, bi-directional, but not very quiet



Shaft-mounted propeller fan
(4-6 dB noise reduction)



Sirocco fan
(low noise, high efficiency, high pressure, unidirectional)



Propeller fan
(low noise, high efficiency, high pressure, unidirectional)

Special considerations

1. Hot spots and excessive losses

- Smearing of lamination in the slot or on the rotor surface
- Irregular shoring of rotor bars to laminations in the slot area
- Poor stacking of lamination, too loose or too much burr or lack of symmetry
- Very tightness of fit between rotor bar and lamination
- Nonuniform loss distribution in the lamination caused by poor annealing or out of control lamination processing
- Improper lamination design
- Bad bar to end ring connections

Test approaches

- Rotor core loop test
- Growler test
- Single-phase rotational test
- No-load saturation test
- Running test for open or broken bars
- Temperature-sensitive paints
- Ultrasonic testing

2. Rotor sparking

Nondestructive sparking

During cross-the-line starting, the current in the rotor cage can be 5-7x normal, which will cause a voltage drop along the length of the bar in excess of 6x the normal running value. It is this voltage that tend to send current through laminations. In short, during startup, there are actually two parallel circuits–one through the rotor bar, and the other through the lamination.
The magnetic forces created by the high current flow during startup cause the rotor bars To vibrate at a decaying frequency, starting at 60 Hz, which produces a force of 120 Hz Vibrations. This primarily radial vibration within the confines of the rotor slot causes Intermittent interruptions of the current flow between the bars and various portions of Lamination with resultant visible arcing.
The brief period of intensified sparking that can occur during starting is not detrimental to motor life. Motor with more than 20 years of this operation have been disassembled To reveal only a slight etching of the rotor bars at areas of contact with the core iron.

Destructive sparking

Destructive sparking can occur under several circumstances, the most common being a broke rotor bar or defective bar-to-end-ring connection.

The common methods to determining the sparking due to broken bars or end ring connections:

- Visual inspection of all rotor components (i.e., bars, rings, laminations, shaft, and fans)
- Tapping the bars with a mallet (loose or broken bars have a distinct sound)
- Current pulsation when unit is under load
- Single-phase rotational test
- Growler test
- Observed noise (rattling sound) during starting cycle

3. Unbalance magnetic pull and rotor rub

- Unbalance magnetic pull is a potential problem which can cause the rotor to bend and strike the rotor stator winding.
- The reasons are things, such as eccentricity, rotor weight, bearing wear and machine alignment.
- The acceptable amount of eccentricity is in the range of 10% ~ 20% the air-gap, depending upon the size of the machine. In conjunction with this, the shaft size is selected, based on its ability to resist these bending forces (shaft stiffness).
- The potential for rotor pullover can be described as function of the air gap, concentricity, stack length, air-gap flux density, and staring cycle when the ampere-turns are also greatest.
- A visual inspection of the parts is the best way to confirm that this condition exists and how serious it was.
- The most common method of correction involves improving the air gap geometry by boring the stator and/or turning or centering the rotor OD.

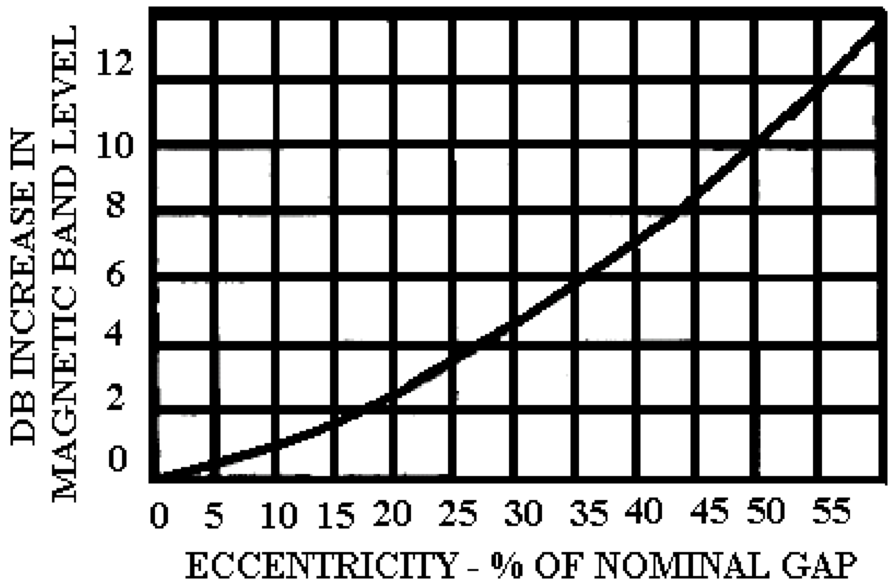
4. Electromagnetic noise and vibration

- Air-gap eccentricity can cause noise and/or vibration problems.
- The radial force produced by the stator harmonics combine with those produced by the rotor harmonics and can create electromagnetic noise and/or vibration.

- Five basic types of air-gap eccentricities:

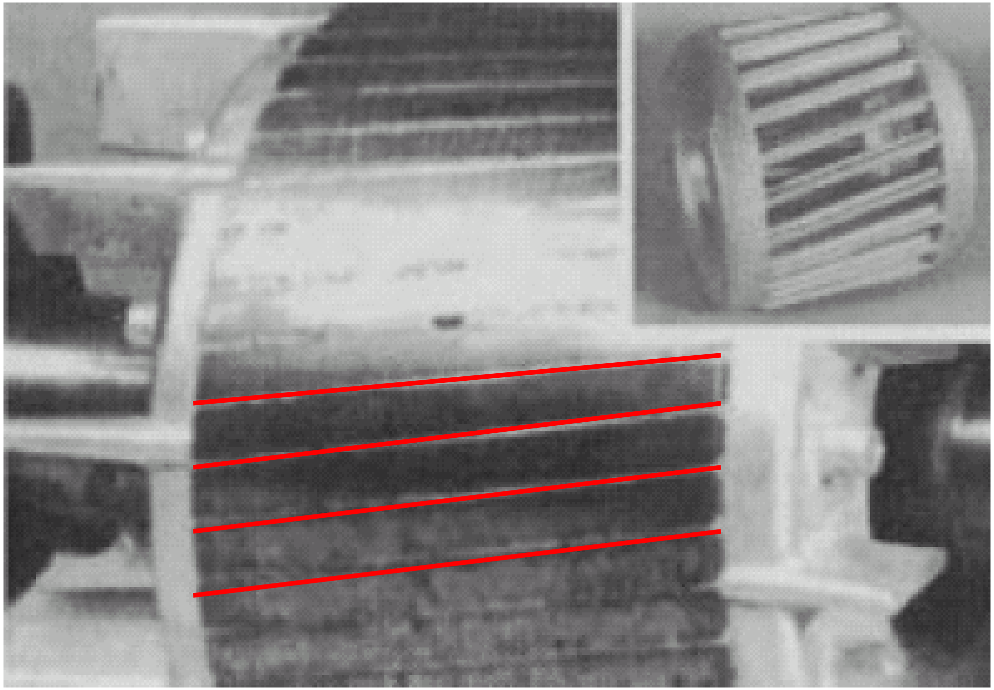
1) Rotor OD is eccentric to the axis of rotation
2) Stator bore is eccentric
3) Rotor and stator are round, but do not have the same axis of rotation
4) Rotor and shaft are round, but do not have same axis
5) Any combination of the above can occur.

Eccentricity versus noise level (dB)(magnetic band)



Courtin conducted a series of test on NEMA-size open drip proof motors and developed the above curve to indicate the relationship between air-gap eccentricity and noise. It has been the authors' experience that motors with severe air-gap eccentricity (over 25%) will contribute 2-3 dB to the overall noise level on the machine.

5. Skewing

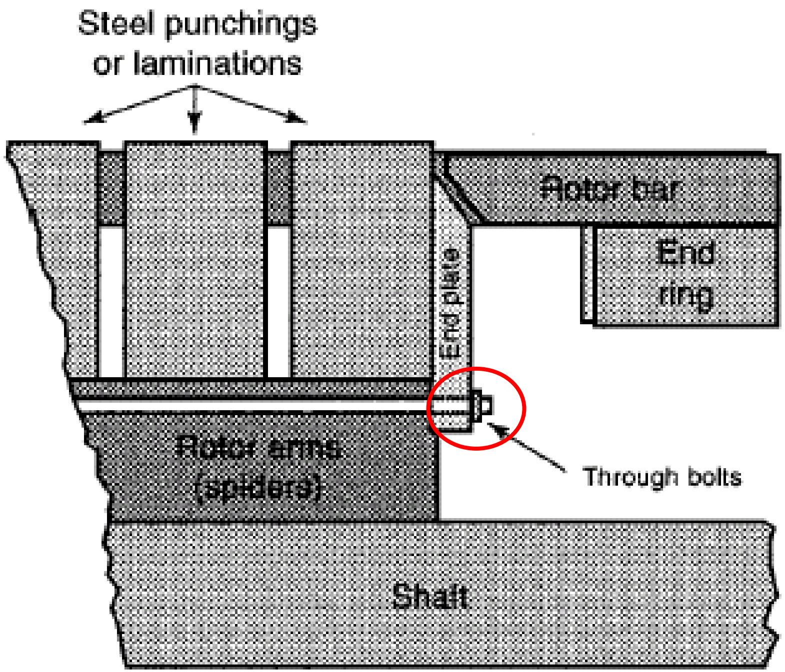


- Skew is an angular twist of a slot away from the axial direction.
- Typical skew is one stator slot pitch.
- The purpose of the skew is to reduce spatial harmonics in the air-gap flux that are introduced by a finite number of slots and the slotting combination.

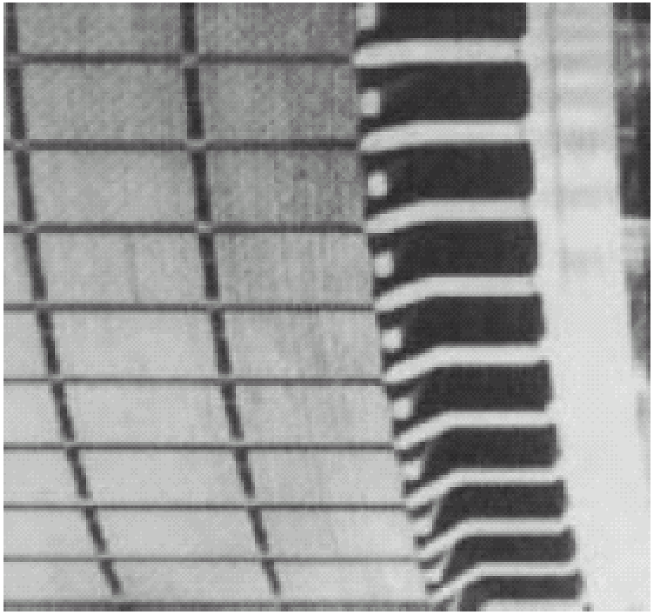
Typical results of skewing are as follows:

- Reduction of induced EMF in bar, improved voltage waveform
- Higher rotor leakage reactance and less torque
- Skewed bars have a current that has a circumferential component which develops a small axial force which imposes additional load on bearings
- Nonuniform air gap flux increases core and stray losses
- Improved speed-torque characteristics, including elimination of locking torque at zero speed and cusps at various speeds
- Reduced likehood of electrical noise problems

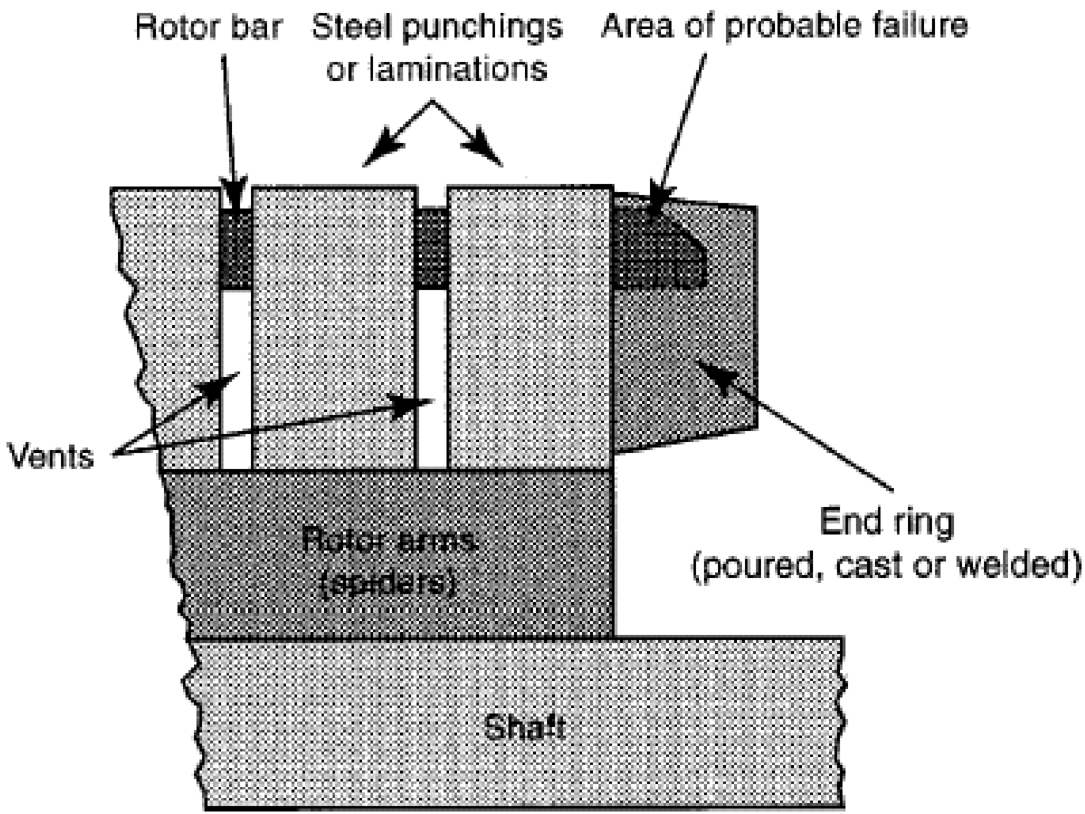
Aluminum versus copper construction preference



End ring/bar construction
for a typical fabricated copper bar rotor



A typical large fabricated copper bar rotor with butt-welded end ring



End-ring construction

for a typical fabricated aluminum bar rotor

Comparison of cast versus fabricated rotors

Item	Cast Aluminum	Fabricated Aluminum	Fabricated
Bar Material (Conductivity)	Lower temperature melts at 1220° F Aluminum or alloy (55% Conductivity)	Many Sizes (50% - 55% Conductivity)	Many choices of material .highest temperature melt at 1981°F (20% - 100% Conductivity)
Design Flexibility	Virtually unlimited bar shape Multiple cage construction possible Long rotors difficult	Limited bar designs available Single cage normally Easier open slot design	Limited bar designs available Single cage normally, longer then all Easier open slot design
Manufacture	High capacity/short cycle time Longer stacks and larger diameter are hard to cast	Low capacity/longer cycle time Low capital investment	Low capacity/longer cycle time Low capital investment
Inertia WK^2	Average (high rotor weight)	Good (heavier load capability)	Very good (high inertial loads)
Casting Porosity	Some porosity concerns in casting	None Welding technique critical	None Welding technique critical
Manufacture Cost	Lowest cost	Higher cost – labor intensive	Highest cost – material and labor
Electrical Performance	Good, consistent Surface smear on open slots a concern Porosity can cause lower eff. and torques	Aluminum is very good	Copper is excellent
Bar to Lamination Insulation	Core plate provides insulation between bar and lamination	Can insulate aluminum bar by anodizing	Usually one

Rotor Options for Squirrel-Cage Induction Motors

Feature/item	Cast Aluminum	Fabricated Aluminum	Fabricated
Tooling Cost Initial	Highest Die-cast equipment and tooling	Minimum	Minimum
Maximum Size	Varies, but limited length and diameter	No size limit if thermal stability is maintained	No size limit
Mechanical Construction	Compressed with die-cast and rings & fan	Cast end rings with attached fan blades Could limit overspeeds	Welded end rings & attached fan blades Could limit overspeeds
Reliability	Very high Loose, cracked or broken bars rare	Good Cast end rings help prevent bar motion Swedge helps prevent bar movement	Good Welding process is critical to reliability Swedge helps prevent bar movement
Stability	Excellent	Good	Good
Bar Shape	Very flexible shapes Limited by tooling cost	Limited by extrusion die shapes	Very limited shape options Machined bars very expensive
Starting Ability	Excellent speed-torque curve	Good torque / amp	Best for high inertia load
Life Factor	Excellent	Good Tight bar fit must be maintained	Good Tight bar fit must be maintained
Heat Transfer	Best –three times fabricated	Lowest	Low
Skew	Easy and consistent	Expensive	Expensive
Repairable	Difficulty to impossible, could be fabricated	Possible	Easiest