Recent developments in Copper Rotor Motors in China

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Abstract

This paper mainly focuses on the recent progress in the: optimization of the production process, development of high efficiency copper rotor motors as well as new copper rotor motor standards in China. Optimization during the casting process makes it more economical to produce high quality copper rotors via casting. The development of IE3 and IE4 copper rotor motors are introduced, and the detailed performance analysis is given. The new national standards for super efficiency copper rotor motors and flame proof copper rotor motors are also introduced.

1. Introduction:

Squirrel cage induction motors are the mostly used motors at present. Squirrel cage induction motors took a share of over 85% of the total middle and small motors output in 2007 in China[1]. Currently, squirrel cage induction motors are widely applied in industries, agriculture, national defense, commerce, public facilities and transportation, becoming an inseparable core motors for all kinds of industries.

Currently, the rotors of the squirrel cage induction motors are produced by aluminum die casting technique with the advantages of high efficiency and low cost of rotors. It is known that the copper's conductivity of electricity is around 40% higher than that of aluminum. If copper is used to replace the current widely used aluminum cast rotors, the total loss of motors will be reduced obviously, hence increasing the overall efficiency of motors. Copper rotors can produce high efficient and even super premium motors, hence higher energy efficiency of motors of the same size. Redesign of motor's rotors and stators in line with the property of cast copper rotors can maximize the efficiency to reach higher or even super premium energy efficiency.

While reducing the motor losses, the coil temperature of rotors and stators will be lowered due to the fact that the amount of energy transferred into thermal energy has been reduced. Lower temperature means that smaller fan can be used or with no fan at all, a move that reduces the friction loss and air resistance of additional components so as to improve the motor's efficiency. At the same time, reducing motor's working temperature will greatly extend the life expectancy of motors and lower maintenance fee. Normally, 10 degree Celsius of temperature reduction of motors can double the life expectancy of insulated materials. Under normal maintenance conditions, motors with copper rotors enjoy a longer usage period and higher reliability.

Because copper's electrical resistivity is low, electric current in the rotors of the same induction voltage is bigger than that of aluminum rotors; therefore fewer materials can be used to produce motors with the same power and efficiency. It is because of the material used has been reduced, cast copper motors of the same power and efficiency will enjoy lower material cost, lighter weight and smaller volume than the conventional motors. At the same time, the excellent anti-corrosion features of copper can make cast copper motors have better environmental tolerance and reliability. All the advantages provide a broader and more flexible design space for motor designers and producers, making them pursue higher efficiency, lower cost, smaller volume and lower weight or strike a balance among all the factors.

The above mentioned excellent features of cast copper rotor motors make the motors enjoy a broad application in ordinary industrial motors, electric vehicles, hybrid vehicles, submersible pump motors, swimming pool circulation pump motors, crane motors, aviation control motors, high speed spindle motors, nuclear station motors, military used special motors and small wind power generation motors.

Die casting of pure copper is the obstacle of promoting the large application of cast copper rotors, a difficulty caused by high melting point of copper. The melting point of pure copper (1083ºC) is much higher than that of aluminum (660ºC). But in the actual production, the pouring temperature of copper liquid is as high as 1200°C which has a demanding requirement for the anti-high temperature property of the mould materials. If the current aluminum die casting mould is used for cast copper rotors, the life expectancy is just 1/100th of the cast aluminum. The too high die casting temperature will lower the life expectancy of moulds and hence increase the cost of producing cast copper rotors, becoming a major obstacle of promoting cast copper rotors. [2]

To deal with it, International Copper Association began to conduct relevant researches starting from 1994 and made a series of progress. In China, International Cooper Association worked with Yunnan Copper Die-die casting Technology Co., Ltd and Nanyang Explosion Protection Group Co., Ltd to launch the commercial production of copper rotors. Currently, the two companies have began to producing high quality copper rotors, churning out more than 60 types of high quality cast copper rotors with different specifications for 15 clients.

This article will elaborate on the latest development of cast copper rotors in China, including the improvement of die casting techniques, the R&D of super premium motors, R&D of special motors and the promulgation of standards for die casting copper rotors.

2. The improvement of die casting technique:

The production of large scale and economic copper rotors by die casting has the following 3 difficulties:

A. Melting technology of pure copper

Since copper is easy to be oxidized under high temperature, it is easy to prevent the oxidation of copper liquid in laboratories, but more difficult to do so in plant (large scale commercial production). As the content of oxide in copper has a direct bearing on the electric conductivity of copper, therefore failure to control the oxidation of liquid copper will greatly reduce the conductivity of copper, seriously affecting the property of motors.

B. Copper casting process

The crystal structure and metallurgy property of pure copper make copper casting difficult, at the same time in the process of actual casting, the casting process needs to be optimized to reduce the possibility of flaws such as air vent so as to improve the quality of rotors.

C. Mould

In the aspect of mould, the selection of mould materials and design need to be considered. High property of mould materials and optimized design of mould structure can offset the impact of high temperature copper liquid on mould’s property so as to improve the life expectancy and reduce production cost.

In response to the above mentioned issues, International Copper Association has helped Yunnan Copper Die-die casting Technology Co., Ltd and Nanyang Explosion Protection Group Co., Ltd to do relevant researches and put forward the solution of producing cast copper rotors based on horizon casting machine. Currently, cast copper rotors have been produced massively based on this solution which includes the followings:

A. Melting technology of pure copper: melting system, feeding system, and innovative methods of protecting pure copper from oxidation.

B. Copper casting process: die casting simulation software of pure copper based on horizon casting machine and the control of casting parameters.

C. Mould: several types of innovative mould materials suitable for pure copper die casting, simulation software of mould temperature field and fresh new mould structure design.

Thanks to the innovative improvement, currently, the solution based on horizon die casting machine can greatly prolong the life expectancy of mould and reduce production cost and improve the product quality. As shown in figure 1:

Figure 1, internal quality of cast copper rotors

Currently, the solution based on horizon casting machine has been mature and entered into commercial and mass production.

3. The development and property analysis of super premium cast copper motors:

It is beyond doubt that the use of cast copper rotors is the simplest and the most economically reliable way of improving motor efficiency. In China, we have successfully developed NEMA Premium series and IE3 series of super premium cast copper motors based on cast copper rotors. Table 1 shows the NEMA Premium motors series.

Table 1, NEMA Premium CMR motor series

Frame Size	Pole	Rated Power (kW)
140	4	0.75

		1.1
		1.5
	6	0.75
180	4	2.2
		3.7
	6	1.1
		1.5
210	4	5.5
		7.5
	6	2.2
		3.7
250	4	11
		15
	6	5.5
		7.5

Table 2 gives IE3 series CMR motors.

Table 2, IE3 efficiency CMR motor series

Frame Size	**Pole**	Rated Power (KW)
80	2	0.75
		1.1
	4	0.75
90	2	1.5
		2.2
	4	1.1
		1.5
	6	0.75
		1.1
100	2	3
	4	2.2

		3
	6	1.5
112	2	4
	4	4
	6	2.2
132	2	5.5
		7.5
	4	5.5
		7.5
	6	3
		4
		5.5
160	2	11
		15
		18.5
	4	11
		15
	6	7.5
		11
180	2	22
	4	18.5
		22
	6	15
200	2	30
		37
	4	30
	6	18.5
		22

In the trial production, we found that motors with cast copper rotors are easy to reach the efficiency of NEMA Premium (IE3) or higher efficiency, as shown in the following chart. This is very important to the small and middle motor producers. Due to lack of sufficient R&D capability and high quality of silicon steel sheet and precision control over production process, producing NEMA Premium (IE3) motors with conventional cast aluminum rotors is more difficult for small and middle motor producers, especially for those in developing countries like China. While cast copper rotors have provided them with a simple and economic way of producing more efficient and super premium motors.

Table 3, Efficiency measured by IEEE122B

Type	NEMA Premium Standard	Copper Rotor Motor
143T- 4 1HP (0.75kW)	85.50%	86.2%
182T- 4 3HP (2.2kW)	89.50%	91.04%
213T-4 7.5HP(5.5kW)	91.70%	92.68%

Through the R&D of NEMA Premium and IE3 series super premium cast copper rotor motors, we found that super premium cast copper rotor motors have the following index properties. We will take IE3 series motors as the example to introduce the test performance as following.

We have set whole sets of performance goal to begin the development which includes efficiency, operational temperature, power factor, Max torque, locked torque and locked current.

A. Efficiency

Efficiency will be in accordance with the standard of IE3 50Hz in IEC60034-30 and the test method for efficiency will follow IEEE112 B.

B. Temperature increase, vibration and noise

The resistivity of copper is around 60% of aluminum which can effectively reduce the losses of rotors. At the same time, copper bar has better heat conductivity than aluminum bar; therefore the use of cast copper rotors can effectively reduce temperature increase, external diameter and noise. The temperature increase, vibration and noise standards shall be consistent with that of YX3(Chinese standard motor, roughly IE2)

C. Power factors

According to the previous trial production of cast copper motors, power factors have the trend of being reduced and it is obviously clear within 0.75kW-7.5kW. The reduction of power factors can be contributed to the higher efficiency, improvement of initiation property and availability of effective materials. In addition, the great improvement of efficiency of small power frame and the adoption of different methods to increase efficiency have resulted in the great reduction of power factors. This can be seen from experimental data of other high efficient and super premium motors.

The power factor indices have been lower compared with YX3 series, the following table is the comparison:

Table 4, Power factor standards comparison of YX3 series and cast copper rotors

Power (KW)	Motor Types	Synchronous Rational Speed (r/min)		
		3000	1500	1000
0.75	YX3series	0.83	0.75	0.72
	Cast copper motors	0.82	0.7	0.68
1.1	YX3series	0.83	0.75	0.73
	Cast copper motors	0.82	0.7	0.68
1.5	YX3series	0.84	0.75	0.74
	Cast copper motors	0.83	0.7	0.69
2.2	YX3series	0.85	0.81	0.74
	Cast copper motors	0.84	0.75	0.72
3	YX3series	0.87	0.82	0.74
	Cast copper motors	0.86	0.81	0.72
4	YX3series	0.88	0.82	0.74
	Cast copper motors	0.87	0.81	0.72
5.5	YX3series	0.88	0.82	0.75
	Cast copper motors	0.87	0.81	0.74
7.5	YX3series	0.89	0.83	0.78
	Cast copper motors	0.88	0.82	0.74
11	YX3series	0.89	0.85	0.79
	Cast copper motors	0.89	0.85	0.77
15	YX3series	0.89	0.86	0.81
	Cast copper motors	0.89	0.86	0.81
18.5	YX3series	0.89	0.86	0.81
	Cast copper motors	0.89	0.86	0.81
22	YX3series	0.89	0.86	0.82
	Cast copper motors	0.89	0.86	0.81

D. Max torque Multiple

The value of the max torque multiple and the overloading capacity of characterization motors. The improvement of the torque will increase the motor capacity of fending off over loading. The max torque of cast copper motors is relatively higher than YX3 series; therefore it is improved than YX3 series while identifying the max torque index. The average value of YX3 series is 2.2

times, that of the cast copper motors is 2.4 times, 10% higher than YX3 series. The details are in table 5:

Table 5, Comparison of the max torque multiple standard value of YX3 series and cast copper motors

Power (KW)	**Motor Types**	**Synchronous Rational Speed (r/min)**		
		3000	1500	1000
0.75	YX3series	2.3	2.3	2.1
	Cast copper motors	2.5	2.8	2.6
1.1	YX3series	2.3	2.3	2.1
	Cast copper motors	2.5	2.8	2.5
1.5	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.7	2.4
2.2	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.5	2.3
3	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.5	2.3
4	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.4	2.2
5.5	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.4	2.2
7.5	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.4	2.2
11	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.4	2.2
15	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.4	2.2
18.5	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.4	2.2
22	YX3series	2.3	2.3	2.1
	Cast copper motors	2.4	2.4	2.2

E. Locked torque multiples and locked current multiples

Since copper's resistivity is lower than that of aluminum, with the adoption of cast copper rotor, the resistivity of rotors will be reduced while the efficiency of motors will be increased greatly. However, the locked torque of motors will be lowered accordingly and locked current multiples will increase. Therefore, rotor trough must be optimized to form rotor punching suitable to the features of cast copper so as to ensure the locked performance of cast copper motors. The locked torque multiples and locked current multiples of cast copper rotors should be consistent with YX3 series.

The typical sample cast copper rotor motors has 8 specifications, 16 sample machines. The following is the result of all the indices trial production:

A. Power factors

Seen from Table 6, 5 of the 8 specifications are qualified, accounting for 62.5%. The tolerance of 3 specifications is qualified, accounting for 37.5%.

Low power factor means bigger losses in cable and transformers, reduced power compactor available for transformers, breakers and cables and higher voltage drop. US NEMA MG1 standard does not have evaluation indicators for power factors but recommend the calculation method and application of power compactor content for compensated power factor.

The expenditure of setting up power factor compensator accounts for only 1%-3% of the total cost (operational fee plus manufacturing cost). The use of reactive power compensation will reduce the losses in the network, fully utilize the power capacitor, effectively lower turbulence of voltage and help motors operate within the designed voltage drop attachment.

Table 6, Comparison of actual test value and guarantee value of power factors of super premium cast copper rotor motors

Type	0.75kW-6	1.5kW-4	2.2kW-6	3kW-2	5.5kW-6	7.5kW-4	7.5kW-6	22kW-4
Guarantee value	0.68	0.7	0.72	0.86	0.74	0.82	0.74	0.86
Allowable value	0.63	0.65	0.67	0.84	0.70	0.79	0.70	0.84
Actual tested average value	0.675	0.681	0.700	0.865	0.740	0.840	0.802	0.862
Qualification	Tolerance Qualified	Tolerance Qualified	Tolerance Qualified	Fully Qualified	Fully Qualified	Fully Qualified	Fully Qualified	Fully Qualified

B. The max torque multiples

Seen from the max torque data in Table 7, the actual max torque multiples are fully qualified. The average guarantee value of max torque multiples of YX3 series motors is 2.4 times, while the average actual tested max torque multiples is 2.89 times, exceeding over 20% of the guarantee value and meeting the requirement for the max torque in NEMA C design of US NEMA MG1, demonstrating that the overloading capacity of cast copper rotor motors is much stronger than that of the conventional ones.

Table 7, Comparison of actual test value and guarantee value of the max torque multiples of super premium cast copper rotor motors

Type	0.75kW-6	1.5kW-4	2.2kW-6	3kW-2	5.5kW-6	7.5kW-4	7.5kW-6	22kW-4
Guarantee value	2.6	2.7	2.3	2.4	2.2	2.4	2.2	2.4
Allowable value	2.3	2.4	2.1	2.2	2.0	2.2	2.0	2.2
Actual tested average value	2.8	3.1	2.9	3.1	2.92	2.75	2.9	2.7
Qualification	Fully Qualified	Fully Qualified	Fully Qualified	Fully Qualified	Fully Qualified	Fully Qualified	Fully Qualified	Fully Qualified

C. Locked torque multiples

Seen from Table 8, 4 of the 8 specifications are qualified, 4 of them are qualified in tolerance, accounting for 50%, meaning that the optimized torque trough of super premium cast copper rotors can meet the assessment of locked torque multiples for ordinary motors.

Table 8, Comparison of actual test value and guarantee value of the locked torque multiples of super premium cast copper rotor motors

Type	0.75kW-6	1.5kW-4	2.2kW-6	3kW-2	5.5kW-6	7.5kW-4	7.5kW-6	22kW-4
Guarantee value	2.1	2.3	2.1	2.3	2	2	2.1	2.2
Allowable value	1.8	2.0	1.8	2.0	1.7	1.7	1.8	1.9
Actual tested average value	2	2.5	2.3	2.1	2.1	1.9	2.3	2.1
Qualification	Tolerance Qualified	Fully Qualified	Fully Qualified	Tolerance Qualified	Fully Qualified	Tolerance Qualified	Fully Qualified	Tolerance Qualified

D. Locked current multiples

Seen from Table 9, 6 of the 8 specifications are fully qualified, accounting for 75%. 4 of the specifications are qualified in tolerance, accounting for 25%. The actual tested locked current multiple is averagely 10% lower than the guarantee value, meaning that the locked current value has a better performance.

Table 9, Comparison of actual test value and guarantee value of the locked current multiples of super premium cast copper rotor motors

Type	0.75kW-6	1.5kW-4	2.2kW-6	3kW-2	5.5kW-6	7.5kW-4	7.5kW-6	22kW-4
Guarantee value	5.8	6.9	6	8.1	7.1	7.4	6.7	7.8
Allowable value	7.0	8.3	7.2	9.7	8.5	8.9	8.0	9.4
Actual tested average value	5.6	6.5	6.4	7.2	6.2	5.6	7.06	6.8
Qualification	Fully Qualified	Fully Qualified	Tolerance Qualified	Fully Qualified	Fully Qualified	Fully Qualified	Tolerance Qualified	Fully Qualified

From the analysis of the actual tested data of motors, we can find that when the cast copper rotor motors reach to IE3 super premium efficiency, the max torque multiples have shown an obvious increase with stronger overloading capacity. The locked current multiples are lower than conventional assessment value, the locked torque is stable and the motor has a better start-up performance. Power factors have been reduced to a certain extent but can be offset by power compensators. It can be said that the main technical indicators of super premium cast copper rotor are relatively reasonable after being proved in theory and in practice.

4. New standards of cast copper rotor motors

International Copper Association has developed in the China's motor manufacturing enterprises alliance the two standards for cast copper rotor motors with super premium efficiency meeting with the requirement of IE3 standard, namely YZTE3 series standard for super premium cast copper rotor motors, and explosion protection standard for YZBT series super premium cast copper rotor motors. The two standards will greatly promote the application of cast copper rotor technology in China. The following is the introduction of the standards.

A. YZTE3 standard for super premium cast copper rotor motors

The standard is for small power motors with the synchronous rotational speed of 3000, 1500 and 1000r/min (the correspondent pole is 2, 4, and 6) and the power range is from 0.75-37kw in order to meet market demand.

1. Power grades of the series products:

   0.75kW • 1.1kW • 1.5kW • 2.2kW • 3kW • 4kW • 5.5kW • 7.5kW • 11kW • 15kW • 18.5kW • 22kW • 30kW • 37kW •

2. The correspondent power range for correspondent rotational speed (or pole)

   Pole 2, 0.75 • 37kW

   Pole 4, 0.75 • 30kW

   Pole 6, 0.75 • 22kW

3. Selection of installation size

   In order to be replaceable with the current products and promoted fast into the market, the installation size of 50Hz series motor should follow relevant regulations in Size and Output Power Grade of Rotary Motors • GB/T4772.1-1999 • and IEC60072.

B. Standards for YBZT explosion protection super premium cast copper rotor motors

The basic parameters of the standard are as follows •

1. Frame size • 80-200 •

2. Rated power • 0.75kW, 1.1kW, 1.5kW, 2.2kW, 3kW, 4kW, 5.5kW, 7.5kW, 11kW, 15kW, 18.5kW, 22kW, 30kW, 37kW

3. Pole • 2, 4, 6

4. Frequency • 50Hz

5. Voltage • 380V • 660V • 380/660V

6. Installation method, size of motors and tolerance: consistent with YX3 series

7. Rated value • Constant working S1

8. Cooling method • IC411, TEFC

5. Conclusion

Through the above introduction, we know that motors and motor system have a great energy saving potential, and cast copper rotor is the simplest and most effective way of improving motor efficiency. In China, the process of producing cast copper rotors based on horizon casting machine has been mature and proven, producing massively cast copper motors with economics. At the same time, the promulgation of national standards for cast copper motors can greatly boost the large scale promotion of cast copper motors. Against the backdrop of fully utilizing energy and sustainable development, the adoption of cast copper rotors will greatly improve the efficiency of motors and motor systems and also promote the wide application of cast copper rotors in motors and motor system.

Reference

[1] Motor market research, Sino-Trust, 2008.

[2] Daniel Liang, David Zhao, Victor Zhou, A Report on Analysis of the Performance and Cost of Energy Efficient and Super Efficient Copper Motor Rotor Based Motors, EEMODS'07 Conference Proceedings, Volume II, 2007, pp567-569.

TECHNICAL-ECONOMICAL ANALYSIS OF THE USE OF DIE CAST COPPER ROTOR IN NORMALIZED INDUCTION MOTORS

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ABSTRACT

This article reviews the major technological aspects of the melting processes of both copper and aluminum in the production of induction motors squirrel cage rotors, highlighting the advantages and disadvantages of each one of these technologies. The use of molten copper and die cast aluminum in the rotor cage of induction motors to attend IE1, IE2 and IE3 efficiency classes as defined in IEC 60034-30 are comparatively analyzed. Active material (stator windings, stator and rotor core laminations, and rotor conductors) cost increase values resulting from the use of copper instead of aluminum in the rotor cage and short circuit rings are presented in two approaches: first, considering a simple substitution of die cast aluminum for molten copper in the rotor bars and end rings of a current standard industrial motor design, resulting in an efficiency increase; and secondly, considering the case of an optimized die cast copper rotor motor specifically designed to provide the same efficiency level of an optimized die cast aluminum rotor motor.

INTRODUCTION

For many decades, the squirrel cage induction motors with power rates below 500 kW have been traditionally manufactured using die cast aluminum as the base material to form the rotor bars and short circuit rings. More recently, though, with the increasing concern of designers and engineers in general with regards to energy savings and CO_2 emission reductions, in the pursuit of developing more efficiency products, the possibility of using die cast copper instead of aluminum in the construction of the rotor cage of induction motors has been also considered.

In spite of the greater complexity and higher costs of the copper die casting process (in comparison with the aluminum die casting process), the possibility of finally increasing motor efficiency has been pointed out as a legitimate and sufficient advantage to plainly justify the replacement of aluminum by copper in the manufacturing of induction motors.

The use of molten copper instead of die cast aluminum in the rotor cage of induction motors has been presented by many authors [1] as a means of obtaining the following benefits:

a) Reduction in motor losses around 10-15%, when comparing the average loss levels normally presented by current induction motors conventionally manufactured with aluminum rotor cage with the global losses presented by motors built with copper-made cage rotors;

b) Reduction in the total cost of raw materials, when comparing the aluminum-made rotor cage motor manufacturing costs with the ones relative to a copper-made one especially designed to render the same efficiency levels.

The first mentioned advantage can be verified replacing the die cast aluminum in the squirrel cage rotor bars and rings of a current induction motor design with molten copper, thereby causing an immediate and intrinsic reduction in the Joule losses both in the rotor and in the stator, without any changes in the geometry or other design parameter (windings, lamination stack length, air gap, etc.) of the original motor. According to [2], the reduction in the rotor Joule losses provided by this simple substitution of base materials can achieve values as high as 40%.

The attainment/verification of the second advantage obviously requires utterly new motor designs. For the comparison to be made on a fair basis, specially optimized machines have to be designed to each situation (copper-made rotor cage x aluminum-made rotor cage), each of them with a specific geometry and distinguished design parameters, in a way that the desired performance - that is, the same efficiency level in both cases - can be achieved with the lowest possible raw material costs with regards to the motor active material in each case.

The aforementioned points were evaluated by means of analytical calculations of industrial three phase induction motors manufactured with rotor cages made of die cast aluminum or molten copper. Machines of several power rates, frame sizes and efficiency classes were considered in this study, namely 0.75 kW (IEC 80 frame size), 4 kW (IEC 112M frame size) and 15 kW (IEC 160L frame size) presenting efficiency levels compatible with the IE1, IE2 and IE3 standard efficiency classes (IE-code) defined in IEC 60034-30 [3]. All analyses were accomplished considering motors fed by purely sinusoidal supply with rated frequency 50 Hz and rated voltage 400 V.

PHYSICAL ASPECTS OF COPPER AND ALUMINUM MELTING

In order for the good quality of the injection and the adequate filling of the bars and short circuit rings of the rotor to be assured, the metal flow off temperature in the rotor injection process must be slightly higher than the metal melting temperatures. Table 1 shows approximate values of the melting temperatures of the copper and the aluminum and the temperatures required for the die casting and injection processes so that the quality of the manufactured rotors can be guaranteed in each case.

Table 1 – Temperatures required for the use of copper and aluminum in the manufacturing of electric machines rotors

Metal	Melting temperature	Injection temperature
Copper	• 1083 °C	• 1300 °C
Aluminum	• 660 °C	• 800 °C

These significantly higher temperatures required for the use of copper in the rotor production (in comparison with the temperature values required for the use of aluminum) impose consequent stresses in the tooling materials and in the whole manufacturing process. This way, for the motor production to be able to support the manufacturing of copper-made rotor squirrel cages properly, it is necessary that all the production tooling set be made of special materials able to withstand the higher temperatures involved in the copper die casting and injection processes, when compared to the temperatures dealt with in the production of aluminum-made squirrel cage rotors [4].

It is important to observe that both the aluminum and the copper are metals that present relatively high oxidation rates and this fact implicates consequences for the melting and injection processes of such materials in the rotor cage manufacturing. The aluminum die casting process benefits from the spontaneous formation of an external oxide skin film, which impedes the contact between the molten metal and the outer air, and thus provides a natural protection for the die cast material during the squirrel cage rotor manufacturing.

The copper melting, on the other hand, does not promote the formation of this superficial protective film and this way ends up allowing the molten material to be more susceptible to external contamination. The copper oxide that results from the reaction of the oxygen present in the environment with the molten copper significantly reduces the electrical conductivity of the metal, what negatively affects the motor efficiency later. This aspect makes the squirrel cage manufacturing process much more critical in the case of using die cast copper, because it requires a rigorous and complex operational control of the whole melting-injection chains. Actually to avoid the oxidation of molten copper is relatively easy in laboratory, but not in a manufacturing environment of series production.

As a consequence of the phenomena approached in the previous paragraphs, the copper must be injected in the rotor lamination stack immediately after its melting, while the molten aluminum can be stored in the liquid state in holding ovens (cold-chamber machines), what considerably facilitates the manufacturing process of the rotors.

There are basically three methods to prevent oxidation of the molten copper in large scale copper rotor production [5]:

a) Adding phosphor bronze or zinc into the melting copper as oxygen absorber;

b) Adding a mixture of wood coal, vegetable ash and sodium borate into the melting copper as oxygen absorber;

c) Using nitrogen gas to cover the surface of the melting copper.

Nevertheless, it cannot be neglected that the application of the methods above, especially those related to the addition of oxygen absorbing elements into the melting copper, result in the contamination (reduction of the purity grade) of the copper, consequently reducing the metal electrical conductivity and, thus, the quality of the produced rotor.

TECHNOLOGICAL ASPECTS OF THE DIE CASTING TOOLING

The useful lifetime of the die casting mold manufactured with conventional materials (H13 quality steel), when used for copper injection purposes, is reduced to around 1% of the lifetime verified when the same mold is used for aluminum die casting [5].

Cu injection • 600 shots

Al injection • 50.000 shots

To increase the lifetime of the copper die casting tooling, the die cast mold should be preheated to a temperature around 600 °C. Without this preheating the mold material would be subjected to a thermal shock that could even cause cracks in the tooling, especially the shot chamber (injection cylinder), leading to a drastic lifetime reduction. If no measures are taken in order to improve the die casting process performance, such cracks can start to appear in the tooling after 20 shots. It is yet important to notice that the mold preheating must be made as much as possible in a uniform way, as means to prevent deformation and subsequent maintenance costs [5].

Engineers and researchers worldwide have studied ways of overcoming the difficulties associated with copper die casting, aiming at the maximization of efficiency and economy in the manufacturing processes. Investigations in this sense have been conducted under different approaches, involving mathematical modeling of the die casting toolings, numerical simulations aided by finite element softwares and accomplishment of practical tests with different materials and process conditions, including experiments with thermal steels and nickel-based alloys for high temperatures.

Experience shows that a relatively simple means of increasing the die cast mold lifetime is designing the short circuit ring of the rotor cage as straight as possible, preferably without fins or balancing pins.

TECHNICAL-ECONOMICAL ANALYSIS OF IE1 X IE2 X IE3 MOTORS

In order for the feasibility of using copper as a substitute for the traditional aluminum as base conductive material of the squirrel cage bars and short circuit rings to be evaluated, simulations were made for three-phase induction motors of different power rates, namely 0.75 kW, 4 kW and 15 kW, all of them having 4 poles and operating at nominal conditions (400 V – 50 Hz) fed by sinusoidal supply. The analyses were initially made considering motors built with aluminum rotor cage and afterwards motors built with copper rotor cage, so that these two possibilities could be comparatively evaluated from both the technical and the economical points of view. Motors from IE1, IE2 and IE3 efficiency classes, as defined in IEC 60034-30 standard, were included in the analyses, considering the following situations:

a) Exclusively replacing the aluminum constituting the squirrel cage of the original motor by copper and keeping unchanged the slot geometry and all other parameters from original motor design, such as windings material and configuration, airgap, lamination stack length, short circuit ring dimensions, etc.

b) Changing the whole electromagnetic design of the motor, so that the original efficiency level could be attained with the lowest active material costs in each case (copper cage x aluminum cage). In other words, creating a new motor design specifically optimized for the use of a rotor cage made of die cast aluminum and another absolutely new motor design optimized for the use of a molten copper rotor cage, in a way that both of them attend the efficiency level of the original design (that is, the one presented by the aluminum cage rotor motor of the topic "a").

The objective of the first analysis made (topic "a") was to find out the actual reduction occasioned in the motor losses as a result of the simple replacement of the aluminum for molten copper in the rotor cage. According to [1], this mere operation would cause a global loss reduction around 10% to 15% in the motor, whereas according to [2] the rotor Joule losses would be thereby reduced around 40%. The results obtained in the evaluation made are presented in tables 2 to 6.

Tables 2, 3 and 4 show the variation of the Joule losses in the stator (pj1) and in the rotor (pj2), as well as the total motor losses (pt), when the die cast aluminum in the rotor cage is substituted for molten copper, while all the other parameters of the original electromagnetic design of the motors are kept unchanged. W_Al and W_Cu correspond to the loss values in Watts found for the motor with aluminum cage and the motor with copper cage, respectively.

It is remarkable that the reduction obtained in the total motor losses simply substituting aluminum for copper in the rotor cage reached values around 10 to 13% and also that this operation caused a drastic reduction of the Joule losses especially in the rotor cage, where values even slightly above 40% could be verified.

Table 2 – Joule losses and total losses of IE1 motors originally made with aluminum cage and after the replacement of the aluminum for molten copper

	0.75 kW - 80			4 kW - 112M			15 kW - 160L		
	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.
pj1	142	132	-7.1%	362	341	-5.7%	862	824	-4.4%
pj2	51	29	-43.7%	163	93	-42.8%	320	187	-41.7%
pt	**251**	**219**	**-12.7%**	**746**	**656**	**-12.2%**	**1 718**	**1 548**	**-9.9%**

Table 3 - Joule losses and total losses of IE2 motors originally made with aluminum cage and after replacement of the aluminum by molten copper

	0.75 kW - 80			4 kW - 112M			15 kW - 160L		
	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.
pj1	94	88	-6.6%	340	322	-5.4%	862	823	-4.5%
pj2	39	22	-43.8%	144	84	-41.7%	326	193	-40.9%
pt	**177**	**154**	**-13.0%**	**619**	**548**	**-11.5%**	**1 556**	**1 400**	**-10.0%**

Table 4 - Joule losses and total losses of IE3 motors originally made with aluminum cage and after replacement of the aluminum for molten copper

	0.75 kW - 80			4 kW - 112M			15 kW - 160L		
	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.	W_Al	W_Cu	Var.
pj1	76	73	-4.5%	249	240	-3.4%	613	597	-2.7%
pj2	34	20	-41.3%	116	68	-41.3%	247	147	-40.6%
pt	**155**	**138**	**-11.4%**	**508**	**452**	**-11.1%**	**1 209**	**1 092**	**-9.7%**

Table 5 shows the efficiency levels of the above mentioned motors operating at full rated load. It is clear that the simple replacement of die cast aluminum for molten copper in the rotor bars and short circuit rings brings about a significant increase in the motor efficiency level as a direct consequence of the loss reduction previously presented. One can notice that in some cases this efficiency increase may reach such values that even allow that the motor attend a superior efficiency class as per IE-code. For instance, after the substitution of the rotor cage aluminum for copper, the efficiency level presented by the 0.75 kW motor that originally met IE2 class became similar to the one presented by the original 0.75 kW IE3 motor. Another example of this situation is the 15 kW IE1 motor, which became as efficient as the original 15 kW IE2 motor.

Table 5 – Percent efficiency levels of the motors analyzed in topic "a" operating at rated conditions of voltage, speed and load

	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
	Al	Cu	Al	Cu	Al	Cu
IE1	74.9	77.4	84.3	85.9	89.7	90.6
IE2	80.9	82.9	86.6	87.9	90.6	91.5
IE3	82.8	84.5	88.7	89.8	92.5	93.2

The results presented as yet confirm the advantages advocated by the literature regarding the first situation analyzed, that is, the beneficial outcomes resulting from the simple substitution of the traditional aluminum of the rotor cage for copper without any other change on the current motor design. Tables 2 to 5 show that the loss reduction (and consequently the efficiency gain) promoted by the sole replacement of the conductive material of the squirrel cage from die cast aluminum to molten copper actually occur approximately within the declared limits.

However, a significant production cost increase also takes place as a result of this apparently simple operation of substituting aluminum by copper in the squirrel cage die casting process and this fact cannot be neglected, once that it directly affects both the manufacturer – by the reduction of its possible profit margins – and the customer – by the increase in the final motor price.

Table 6 shows the relations between the active material (lamination steel, copper and aluminum) costs of the motors made with molten copper rotor cage and the motors made with die cast aluminum rotor cage, considering the cost of copper equal to 3.5 times the cost of aluminum, as per the average quotation of these materials in the London Metal Exchange [6] during November 2010. It can be seen that, at such price levels, the active material cost of the motor normally tends to increase more than 30% when the rotor bars and short circuit rings are made of copper rather than aluminum. It is important to notice, though, that the daily quotation of copper has occasionally reached 4 times the quotation of aluminum since December 2010, as show the historic prices charts of the LME. Taking into account, yet further, the availability of these non-ferrous metals in nature, it is clear that copper is a much rarer element than aluminum, what will likely lead to even greater discrepancies between the future price quotations of these materials.

Table 6 – Active material cost relative to the initial design (%)

	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
	Al	Cu	Al	Cu	Al	Cu
IE1	100	137	100	132	100	135
IE2	100	134	100	132	100	132
IE3	100	133	100	131	100	130

The second analysis made (topic "b") aimed at the evaluation of the active material costs of the motors designed for the use of aluminum in relation to the ones of motors designed for the use molten copper in the rotor cage, so that the same efficiency levels of the original motors built with aluminum cage were met in both cases with optimized machines for each situation. According to the literature, developing a differentiated motor design specifically thought for the use of copper in the rotor cage would enable an overall reduction of the raw material costs compared with the ones resulting from a design made considering the use of die cast aluminum in the rotor cage.

The analytical investigation realized to find this issue out was conducted in a way that the copper cage motors were designed to present the same efficiency levels of the initial aluminum cage motors, as per Table 7. For the comparisons made in this study to be fair, however, the designs of the aluminum cage motors had to be also optimized and the costs of active material found for these ones were considered as the reference values for the comparative analyses subsequently made with the active material costs found for the copper cage motors.

Table 7 – Efficiency levels (%) of the motors optimized for the use of aluminum rotor cage and copper rotor cage

	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
	Al	Cu	Al	Cu	Al	Cu
IE1	74.9	74.9	84.3	84.3	89.7	89.7
IE2	80.9	80.9	86.6	86.6	90.6	90.6
IE3	82.8	82.8	88.7	88.7	92.5	92.5

Table 8 presents the relations between the active material costs found for the optimized designs of the aluminum cage motors and the copper cage motors, taking the active material costs of the aluminum cage motors as the reference base.

The results appearing in Table 8 reveal that the active material costs of the motors designed for copper cage rotor use tend to be around 10 to 20% higher than the active material costs of the motors designed for aluminum squirrel cage rotor. It is thus evident that for machines presenting the same efficiency level, provided that this aims at the attendance of the efficiency classes defined as IE1, IE2 and IE3 in IEC 60034-30, the use of aluminum proves to be economically advantageous in relation to the use of copper in the squirrel cage rotor bars and short circuit rings. That is, the supposed general reduction of the raw material cost provided by the use of molten copper in place of die cast aluminum in the rotor cage was not verified even resorting to utterly new optimized motor designs specifically developed for this situation.

Table 8 – Percent comparison between the active material costs relative to the optimized designs of the aluminum rotor cage and the copper rotor cage motors

	0.75 kW - 80		4 kW - 112M		15 kW - 160L	
	Al	Cu	Al	Cu	Al	Cu
IE1	100	118	100	116	100	118
IE2	100	114	100	114	100	118
IE3	100	111	100	117	100	117

In order to verify from which point on it would become effectively interesting from the economic point of view to use die cast copper instead of aluminum in the construction of the rotor cage, an analysis was made hypothetically varying the relative quotations of the aluminum and the copper, considering the aluminum price constant (in other words, only changing the cost of copper in the designs), supposing different scenarios in the international market with regards to the price quotations of the metals in question. This investigation was accomplished with the 15 kW IE3 motor, in order to consider the case involving the highest efficiency levels within the scope of this study. The results obtained in this simulation are graphically shown in Figure 1. As already mentioned, the curves are plotted so that the active material cost of each motor design is normalized based on the active material cost of the motor optimized for aluminum cage that appears in Table 8.

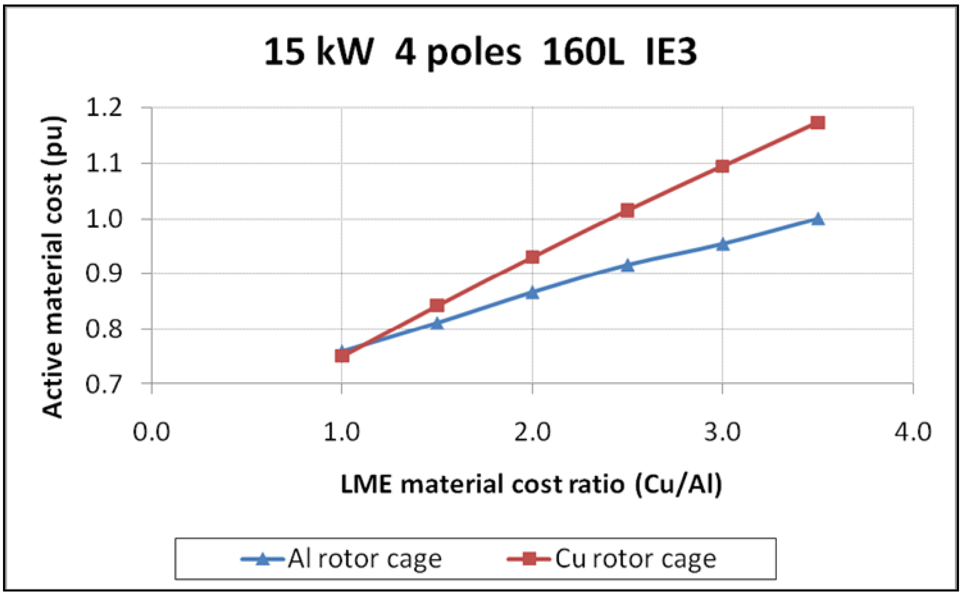

Figure 1 – Relation of the active material costs of a 4-pole 15 kW IE3 motor with rotor cage made of aluminum and with rotor cage made of copper, for different copper/aluminum quotation ratios

Examining Figure 1 it comes out that the active material cost of the aluminum cage motor also decreases with the reduction of the copper price. This happens due to the stator windings, which were considered to be made up of copper wires in all motors analyzed and in this manner the reduction of copper price results in the reduction of the relative cost of the motor windings as well. It can be also noticed that, in this example, the two curves cross when the (Cu/Al) cost ratio is approximately 1.1. This means that, in terms of costs, just taking into account the motor active material, for the adoption of aluminum instead of copper in the manufacturing of the squirrel cage to be worth, considering machines that provide the same efficiency level, the copper purchasing price should not exceed the aluminum purchasing price in more than 10%. Nevertheless, as already mentioned, what has been seen in the international commodities market is the quotation of copper currently reaching values around or even above 300% that of aluminum.

It is important to highlight once more that the cost analyses made in this study did neither embrace any manufacturing process issues nor the costs related to machine components other than the ones related to the active materials themselves, such as the shaft or the motor enclosure. Due to the physical and technological aspects of the copper and aluminum die casting processes, as previously approached in this paper, it is clear that the costs relative to the production of the copper cage motors would result higher than those shown in tables 6 and 8 if the manufacturing process had been also taken into consideration in the analyses made.

CONCLUSIONS

This paper presented a study realized to ascertain the feasibility of manufacturing squirrel cage induction motors using molten copper, as a substitute for the traditional aluminum, as the conductive material constituting the rotor bars and short circuit rings, as an alternative to increase efficiency and reduce costs. The evaluations made were based on analytical calculations, considering two design possibilities: (i) simply replacing the aluminum of the squirrel cage for die cast copper, without changing other design features of current three phase standard industrial motors; and (ii) developing completely new designs optimized for the use of copper in the rotor cage, involving specific characteristics of geometry, windings, stack length, etc., in a manner that the same efficiency levels presented by the original die cast aluminum cage motors were got.

The obtained results showed that the simple substitution of aluminum for molten copper in the rotor cage, without modifying any other parameters of the standard motor design, brings forth a reduction in the motor global losses around 10 to 13% and an active material cost increase around 30 to 40%.

With regards to the investigation conducted to evaluate motors especially optimized for the use of a copper-made squirrel cage, it was found out that their active material costs tend to result around 10 to 20% higher than those of the original motors designed for aluminum cage rotors, when the attainment of the same efficiency levels in both cases is aimed.

The relative cost values mentioned in the paragraphs above were obtained considering a ratio between the copper and the aluminum prices of 3.5, which was the average value observed for the corresponding quotations of these metals during November 2010 in the international commodities market. A case study accomplished with a 15 kW 4-pole IE3 motor showed that, in order for the use of molten copper cage, rather than the traditional die cast aluminum cage, to become economically advantageous in industrial three phase induction motors, the quotation (price/kg) of the copper must be no greater than 1.1 times the quotation of the aluminum.

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