The die-cast copper motor rotor – a new copper market opportunity

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ABSTRACT

Induction motor manufacturers have long known that substitution of copper for die-cast aluminum in the rotor squirrel cage would significantly reduce motor losses and improve the electrical energy efficiency. Aluminum is readily die-cast to produce the complex squirrel cage within and around the iron laminations of the rotor. Copper is much more difficult to die-cast due to its high melting temperature which leads to premature die failure. The work reported here addresses the die life problem in die casting electrical grade copper. A number of candidate high temperature die materials were surveyed. Computer simulation of the cyclic thermal and stress gradients in dies provided insight into the “heat checking” failure mechanism and how it could be minimized or avoided. A nickel-base alloy die system preheated to and operated at ~625°C has been developed and shown to greatly extend die life compared to die steels operated conventionally. A die insert heating and insulation system was developed to make extended runs possible. Copper motor rotors were die cast over a range of machine operating parameters in joint effort with several motor manufacturers. Motor test results showing the predicted 15 to 20% reduction in motor losses and reduced motor operating temperatures are presented.

INTRODUCTION

A short report on the copper motor rotor development was presented at Copper 99 (1). Work to that point had shown that the tungsten alloy, Anviloy, was suitable for die casting electrical grade copper and that certain nickel-base alloys appeared to be promising. The concept of high die preheat and operating temperature to minimize the thermal and strain gradients that result in heat checking of the die surface and eventual die failure was also introduced. Since 1999, the development has been largely completed with extensive experience gained in die casting copper rotors for several motor manufacturers, motor test results have been generated by the manufacturers and the first commercial high efficiency motors have been produced by SEW Eurodrive in Germany. This paper reviews these developments.

Copper Market Potential

Introduction of copper into the rotor of a broad range of induction motors represents a substantial new market for copper. This will be both new copper and recycled high grade electrical grade copper. Estimates of the market potential have been made by CDA Inc. in 1999. Copper in the rotor will be about half the weight of the copper in the windings. In the United States, the high efficiency motors produced under the Energy Policy Act regulations consume 80 to 100 million pounds (36,000 to 45,000 Tonnes). This would mean that adoption of copper for the rotors for this class of motors would be a new market in the U.S. of about 50 million pounds (22,500 Tonnes). The upper bound estimate would be use of copper in the rotors of all motors, or about 200 million pounds (90,000 Tonnes). Meaningful energy savings are realized only in high duty cycle applications, so adoption of copper rotors for all motors is not expected. Word wide consumption of copper in motors is about four times U.S. consumption. This should translate to a potential world market for rotor copper of at least 200 million pounds (90,000 Tonnes).

The German manufacturer of integrated motor drive equipment, SEW Eurodrive, announced in April of this year at the Hanover Fair that they had begun production of a line of high efficiency motors employing the copper rotor and that they plan to convert a large part of their production to this approach to increased electrical energy efficiency. In this company alone, this could mean additional copper consumption of 13 million pounds (5,900 Tonnes).

Technical Justification for the Copper Rotor

The metal chosen for the squirrel cage structure of the induction motor has substantial implications to both motor performance and motor manufacturability. Aluminum has long been the material of choice because the intricate squirrel cage is readily produced by pressure die casting into and around the rotor lamination stack. Electrical grade copper is used in very large (>250 Hp, 200 kW) motors and in some smaller special purpose motors. These are manufactured by a costly and slow fabrication procedure not suitable for production of the millions of integral horsepower and kilowatt motors produced annually. Die casting of the copper would be preferable, but this process has not been economical because of short die life due to copper's high melting temperature.

There is considerable incentive for motor companies to solve the copper die casting problem and offer motors with copper rotors. Motor modeling by several manufacturers has shown that because the electrical conductivity of copper is nearly 60% higher than that of aluminum, motors with copper-containing rotors would have overall loss reductions of 15 to 20% compared to the counterpart aluminum rotor. Very significant energy savings could be achieved. The U.S. Department of Energy reports that motors above 1/6 Hp (1/8 kW) use about 60% of all electricity generated in the United States and that medium power motors (1 to 125 Hp, 0.75 to 100 kW) use about 60% of electricity supplied to all motors (2). A one percent increase in motor electrical energy efficiency would save 20 billion kW-hrs per year or 1.4 billion dollars in electricity (at 7 cents per kW-hr) and 3.5 million barrels of oil in the U.S. These savings would be multiplied several times on a world wide basis.

Use of copper in the rotors in a broad range of sizes of induction motors represents a significant advance in motor technology. This is because the readily available and least expensive improvements to increase motor energy efficiency have been adopted in recent years. Motor losses have been forced down steadily over time, but with diminishing returns as additional increments come at much increased cost. There are few material and engineering options to reach higher efficiency short of suffering greatly increased costs by employing amorphous iron alloy laminations or superconducting windings. Apart from energy efficiency for its own sake, the related benefits of reduced operating temperature and the increased motor life and reduced maintenance costs that follow, are in themselves very important to motor and drive system economics. In addition, analyses by motor manufacturers have shown that the copper rotor can be employed to reduce overall manufacturing costs at a given efficiency or to reduce motor weight, depending on which attribute the designer chooses to emphasize.

COMPUTER ANALYSIS OF HEAT TRANSFER IN DIE CASTING MOLDS

Minimizing Thermal Fatigue Damage

Ideally, the failure mechanism could be mitigated entirely if one could identify a mold material having a low thermal expansion coefficient, high thermal conductivity, low modulus of elasticity, excellent retention of high temperature strength and good oxidation and thermal cyclic oxidation resistance all at the operating temperature of the die (3). Of course, no one material will have all of these attributes, so a list of materials offering promising combinations of these qualities was assembled. A program to screen and assess the materials in pressure die casting trials casting a copper test part was devised.

Results of Modeling Study

A 3-D computer analysis of heat transfer in the die material test inserts vividly showed the thermal gradients generated when the die is brought into contact with molten copper (K. D. Williams, Flow Simulation Services, Albuquerque, NM). This analysis was valuable in understanding the thermal fatigue failure mechanism and how to minimize or largely avoid it. The time to gate freezing and the number of shots to reach the equilibrium temperature profile were also obtained.

Temperature profiles in H-13 die inserts were generated for this material in the test die geometry of Figure 1.

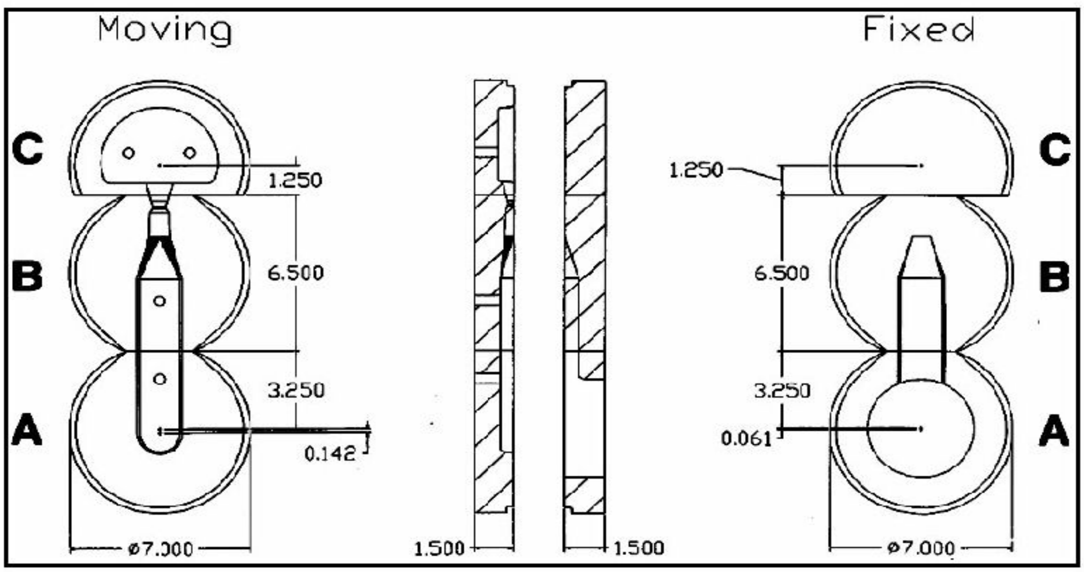

Figure 1 - Die Material Test Die Made up of Six Machined Inserts.

Die surface temperature distributions at the instant of filling with 1200°C molten copper and at points in time immediately thereafter were calculated. Since the die surfaces are generally coated with a mold release compound, a value for the heat resistance, R, of this coating had to be selected. This was taken as 1°Ccm²/watt, a value in the middle of the range found in the die casting literature. To avoid representational problems, the die surface temperatures calculated from the model are shown as though they were "painted" onto the surface of the test casting. An example for the case of the instant of die cavity fill with 1200ºC copper is shown in Figure 2. Representations of this type in color for numerous scenarios are presented elsewhere (4). In this case the casting surface will actually be hotter than the die surface because of the surface heat conducting resistance. In fact, in this example, the investigators assumed that coating the narrow gate region would be difficult and assigned a very low heat flow resistance to this region. Thus the die surface temperature in the gate region was essentially at the melting point of copper. This means that the surface of the gate region of the die insert had risen from the initial temperature of 200°C by 880°C. Because of the low thermal conductivity of H-13 tool steel, the body of the mold was still at 200°C. This implies that the surface had a temperature-induced strain of a least 1.19%, an enormous strain to sustain on a cyclic basis.

Immediately after filling, the coated areas of the die surface were only in the range of 550-600°C, or 350°C above the initial temperature and the bulk of the insert. The surface at the biscuit area at the end of the ram in the shot sleeve was at about 800-850°C.

At 0.5 seconds after casting, results showed that the temperature in the uncoated gate area had started to drop, but the rest of the die surface was getting hotter. The metal volume in the gate is small and with R taken as a very small value in this region, heat diffusion to the die steel is rapid. The longer coated surface areas had risen to the 700 to 800°C range. After 6.5 seconds, it was found that the gate area was relatively cold but coated areas of the larger volume sections of the casting had risen to 750 to 900°C.

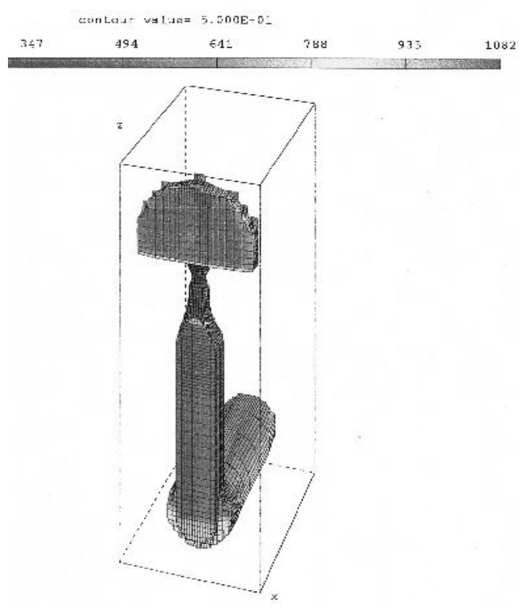

Figure 2 - Output of Thermal Modeling Showing H-13 Die Surface "Painted" onto the Test Casting at Instant of Fill with 1200ºC Copper.

Thus in the H-13 tool steel, we expect from these calculations that the die surface temperature will rise to values ranging from 825°C to over 1000°C everywhere outside the gate region (assumed to be uncoated in this example). These high temperatures occur even with a surface coating with a resistance of 1°Ccm²/watt over these surfaces. These high surface temperatures imply that substantial surface strain occurs everywhere in the H-13 dies.

It was clear that to achieve the higher average mold temperatures required to minimize the ΔT between the die surface and interior associated with each cycle, and the resulting cyclic strain, it would be necessary to both insulate the die inserts from the backing steel and provide a source of heat directly to the inserts. Temperature distribution data of the type shown in Figure 2 was obtained for a tungsten die set with an initial wall temperature taken as 650°C (assuming direct die insert heating and insulation). Although the gate area surface temperature was seen to be near the melting point of copper because of the low surface resistance assumed for this region, the remaining surface temperature was found to be only in the range of 750 to 800°C, only a 100 to 150°C increase. The smaller increase compared to the H-13 example is in part due to the higher thermal conductivity of tungsten.

A model prediction of temperature-time profiles in a tungsten insert preheated to 380ºC was generated using a die/copper contact resistance of 0.3ºCcm^2/watt. This prediction was compared to the measured temperatures during the shot with thermocouples located near the front, center and rear of the insert (4). The agreement was excellent. A ΔT of about 400°C between the front and rear of the insert was generated immediately after filling the die cavity. Calculations showed that this would lead to a small plastic strain on each cycle. For tungsten, the minimum die temperature to assure stress below the yield point and no plastic strain is 550°C. It is important to note that with the ductile/brittle transition temperature being about 200°C for tungsten, the machine operator cannot use the first few shots to achieve the operating temperature without cracking the die.

In nickel-base alloy molds, the temperature gradient and resulting surface stress will be higher due to the lower thermal conductivity of these alloys. The minimum die temperature to assure that cyclic surface stresses remain below the yield point was estimated to be about 625°C.

DIE MATERIAL EVALUATION TESTS

The test castings were pressure die cast at Formcast Development, Inc., Denver, CO in a 660-Tonne real-time shot controlled Buhler horizontal machine using H-13 die inserts. Eight pound (3.2 kg) charges of chopped copper wire rod were inductively melted on a shot-by-shot just-in-time basis with a two minute cycle time to avoid a large holding furnace and the attendant problems of control of oxygen and hydrogen in the molten copper over an extended time. The copper was heated to 1230°C providing about 150°C of superheat.

H-13 Die Steel

An H-13 die set was run to failure to establish a base line and to gain experience in die casting copper. To minimize thermal shock with the first few shots of molten copper, the dies and shot sleeve were preheated to about 350°C with an oxy-acetylene torch. As expected, substantial physical damage was quickly evident after only about 20 shots. The run was continued for a total of 800 shots during which steady deterioration by heat checking, cracking and erosion at insert joints and ejector holes was taking place. The run was discontinued when ejection of the casting became difficult as copper solidified in the deep fissures.

TZM and Anviloy

TZM is a molybdenum-base alloy containing nominally 0.5% Ti, 0.09% Zr and 0.025% C. Anviloy 1200 is tungsten-base containing 4% Ni, 2% Fe and 4% Mo. The alloys were tested simultaneously in the test die configuration of Figure 1. At this point in the die material investigation, the first heated die configuration had been designed and installed on the machine (Figure 3). This allowed preheating and maintaining the dies at 450°C. This was the maximum temperature attainable with this initial heater array design and was about 100°C below the minimum required to avoid exceeding the yield strength at the surface suggested by the thermal modeling. Failure of one or more heaters during the first run of 500 shots resulted in operation at an even lower temperature for a portion of the run. Despite these problems, no heat checking of either alloy was evident but minor cracking of the Anviloy inserts at sharp radii was noted.

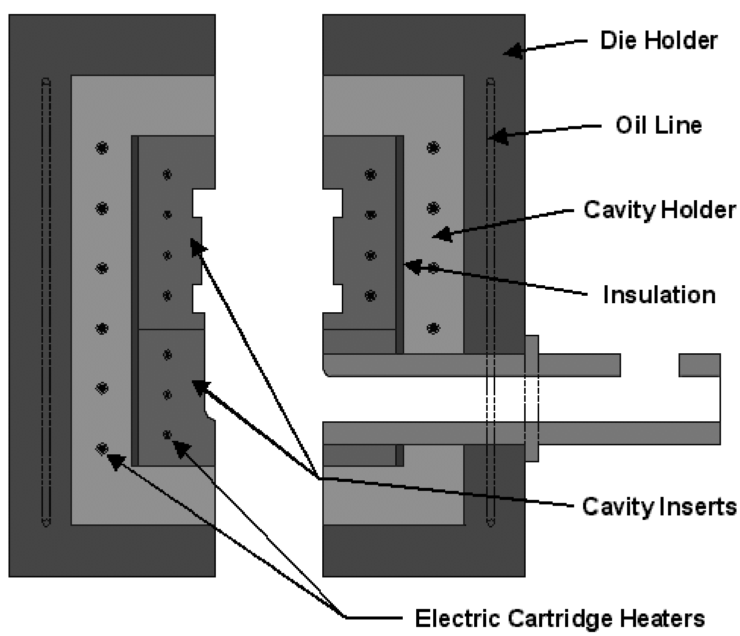

Figure 3 - Schematic Illustration of Placement of Electric Resistance Heaters and Insulation in the Die Material Test Set-up Developed in the Course of this Study.

A second run was carried out some weeks later with all heaters operating extending the total number of shots to 940. At this point, both the TZM and Anviloy inserts showed additional minor cracking at the ejector pin holes due to inadequate allowance for the higher thermal expansion of the steel ejector pins. Otherwise these die sets appeared to be capable of extended runs in this severe copper die casting exercise with no heat checking in the gate areas, contours, and flat surfaces. The TZM inserts did suffer serious surface degradation by oxidation because the surface reached temperatures above 700°C where the oxide melts and volatilizes. This problem makes uncoated TZM a poor choice for die casting pure copper.

This work indicates that with sufficient preheat and maintenance of the operating temperature at 550°C, Anviloy is a suitable die material for die casting of pure copper. High base material and machining costs are deterrents to its use, but Anviloy may offer a viable alternative in a part or parts of the die, such as the runner or gate, where the incoming metal temperature or flow rate are extreme.

Nickel-base Alloys

Three very different types of nickel-base alloys were evaluated with two inserts of each alloy in the test die. INCONEL alloy 617 is a 22% Cr, 12.5% Co alloy solid solution strengthened with 9% Mo. INCONEL alloy 718 is a gamma prime strengthened alloy containing 15.5% Cr, 0.7% Al, 2.5% Ti and 0.95% Nb. INCONEL alloy 754 is a mechanically alloyed 20% Cr alloy with small additions of Al and Ti. A dispersion of Y_2O_3 is the principle strengthener giving resistance to recrystallization and excellent retention of high temperature strength. In a run of 250 shots, the inserts were preheated to 350°C using the electrical resistance heaters and not permitted to fall below this temperature in the cooling portion of the cycle. Even though the 754 alloy has the highest strength at the copper melting temperature, these inserts began to show cracking in less that 50 shots. INCONEL alloy 718 began cracking in about 100 shots. Being a precipitation-hardening alloy, alloy 718 would be expected to have very low strength near the surface which would reach the melting point of copper on each cycle but maintain its high tensile and yield values in the interior and back of the insert where ductility (17-19%) is only fair. INCONEL alloy 617 showed only minor craze cracking after 250 shots at this low operating temperature (275°C below the minimum required). This test served to reveal alloy 617 as having the best combination of strength and ductility over the range of temperatures experienced by the insert.

A second extended run was done to evaluate the solid solution nickel-base alloys, INCONEL alloys 601, 617, and 625. Alloy 601 is a lower strength Ni-23% Cr alloy with l.35% Al. It has only 14% elongation at ll77°C and yield strength of only 15 MPa. Alloy 625 has 21.5% Cr, 9% Mo and 3.65% Nb and has somewhat higher tensile and yield strengths at room and intermediate temperatures, but is not quite as strong at 1100°C as alloy 617. Ductilities of both alloys 617 and 625 are quite high (45% minimum over the range of temperature) but slightly higher in alloy 617. At the point in time of these runs, the array of heaters and insert insulation shown in Figure 3 had been developed to the point that the preheat and operating temperatures could be maintained at 540°C and with further tweaking for the next run, to the 625-640°C range.

In the course of an extended run with this die heating equipment, it became apparent that the amount of heat checking was markedly reduced as the operating temperature was increased. Finally in the last 330 shots at the highest operating temperature, there appeared to be no further deterioration of the die set. A total of 950 shots at the several progressively increasing operating temperatures had been made in this rather severe test. Clear distinctions among the three INCONEL alloys were difficult to discern. Alloy 601 may have somewhat inadequate tensile and rupture strengths for very long campaigns at or near 650°C.

Chemical analysis of several copper test castings showed average iron pick-up of 65 ppm, 5 ppm Ni and 0.074 wt% oxygen. The microstructures were quite sound. The electrical conductivity was higher than that of the castings from the H-13 dies averaging 99.9 % IACS. Elimination of the steel shot sleeve in favor of a nickel-base alloy sleeve would presumably further reduce the iron and increase conductivity slightly.

Conclusions from Die Material Tests

Extended production runs will be required to prove the point, but these tests show promise that the INCONEL alloys 617 and 625 operated in the 600-650°C temperature range are very promising die materials for long die life in large volume production of die-cast copper motor rotors. Although not tested in this study, Haynes alloy 230 is also a strong candidate die material. This alloy has slightly higher yield strength and ductility than alloy 617 and is weld repairable. Alloy 230 has been used in the first copper rotor production die set. An important conclusion from this work is that it is absolutely essential to operate at elevated temperature to extend die life. The higher die temperature reduces the surface-to-interior ΔT on each shot which in turn greatly minimizes the cyclic expansion and contraction and thus the thermal fatigue mechanism causing heat checking and more severe cracking. Temperatures above 650°C are not required and in fact would reduce productivity by increasing time required to cool the die-cast part. A practical die heating and insulation design has been developed.

MOTOR PERFORMANCE TESTS

Introduction

Copper rotors were die-cast at Formcast Development for four motor companies for evaluation in their own facilities. Ordinary tool steel dies were used because only a few rotors were required for testing. These die inserts were mounted in a three-platen master mold assembly of the type conventionally used in rotor die casting. To maintain superheat, a heated shot sleeve surrounded with a thermal wrap was used. The shot sleeves were specifically sized for each rotor size to minimize air entrapment and porosity in the casting. Appropriate weight charges of chopped C10100 wire rod were melted. Melting times and cycle times were somewhat longer than those of the die material tests because of the limitation of the 60 kW power supply available. The cross section of a die-cast rotor is shown in Figure 4.

The real-time shot control capability of the die casting machine provided opportunity to study a number of die casting variables that might affect the quality of the cast copper and the performance of the rotors in motor tests. On the machine used, ram speed can be set at a number of positions and final compacting pressure and duration are adjustable. A wide range of these variables was used to assess the sensitivity of the copper die casting process to machine operating parameters (4).

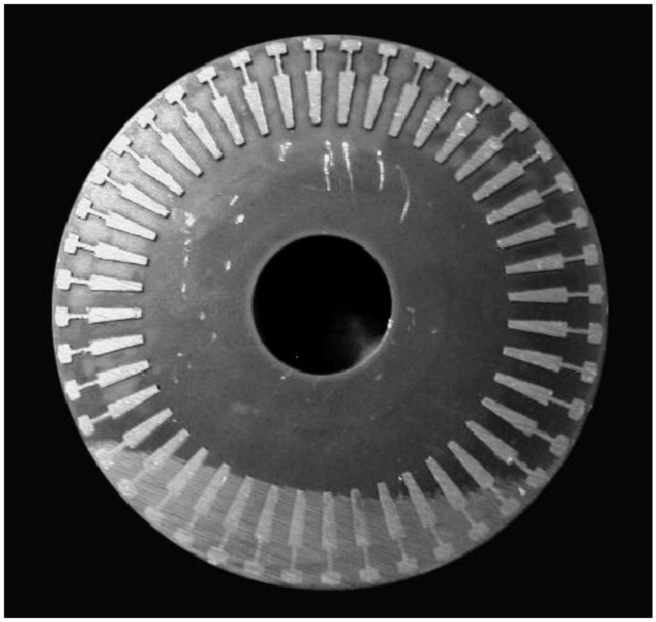

Figure 4 – Photograph of the Cross Section of a Die-cast Copper Rotor

Because copper is so much hotter than aluminum entering the conductor bar channels, there was some concern that the conductor bar might weld to iron laminations or that the properties of the iron would be compromised by heat treatment. Welding of laminations to the copper would increase the magnetic loss component of the total motor losses. On ejection from the machine, half the rotors were water quenched on the theory that rapid cooling would shrink the copper from the iron and would minimize high temperature annealing of the iron. The other half was allowed to air cool.

A total of about 140 rotors were cast for four motor manufacturers for evaluation in their own laboratories. Three companies used dynamometer efficiency tests as per IEEE Specification 112, test method B, as required in the U. S. by the National Electrical Manufacturers Association (NEMA) and the Energy Policy Act of 1992 (EPAct). The fourth company used the IEC 34-2 test method. The IEC method assumes a fixed percentage as stray load losses. The IEEE test method is a true watts in vs. watts out efficiency test that segregates the energy losses into five categories of Iron Core Losses, Stator Resistance, Rotor Resistance, Windage and Friction and Stray Load Losses.

The first four are measured directly and the remainder is in the “stray load” category. For reasons explained below, stray load losses are reduced by the copper rotor and it is therefore important to determine this loss rather than assume a value for it. To ensure an accurate comparison with the corresponding aluminum rotor, a single wound stator was used to test all rotors in each test program.

Participating motor manufacturers were assured confidentiality. Each agreed to disclose test data, but at their request, these companies are not identified.

15 Hp (11.2 kW) Motor

The first copper rotors cast were for a 15 Hp (11.2 kW) motor and were 5.7 inches (144.8 mm) in diameter with a 6-inch (152.4 mm) stack height containing 14 lbs (6.4 kg) of copper in the conductor bars and end rings (13.2 kg charge). It is important to note that the laminations used here were designed for aluminum; i.e. the slot design had not been optimized for copper. A number of rotors were cast covering three different injection pressures and one-half were water quenched.

Seven rotors covering a range of process variables were tested and compared to a large database of similar aluminum rotor motors averaged as a "typical" motor. The same "standard" stator was tested seven times, yielding a spread of stator resistance losses ranging from 502 watts to 522 watts. This represents an approximate plus or minus 2% testing error which was assumed to be applicable across all test data. Applying this logic, the data for stator resistance and core iron magnetic loss have been averaged and considered a constant in both copper and aluminum rotors since they are not affected by rotor material.

Test Results

The test results were remarkably consistent across all process variables. The key measure of efficiency yielded virtually no difference with 90.7% as average and variation of only plus or minus 0.1 percentage points. Rotor watts loss averaged 157 watts with a maximum variation from 153 to 167 watts. With only seven tests, no pattern could be discerned relative to any of the process variables. The conclusion is that the process is very robust and process variations within the range tested have no predictable effect on final performance results. Although the post-casting cooling method seemed to have no effect on the results, water quenching reduced rotor handling time to one minute versus a 20-minute air-cooling time. This would allow much faster production in a manufacturing plant.

From the remarkable consistency of the test results, we conclude that the casting process is practical and reproducible. Results variations were all within test measurement accuracy and no pattern emerged reflecting die casting variables. When compared to historical variation in aluminum rotor motors, these copper rotors were so consistent as to deem the data variation insignificant.

Table I shows the IEEE test results as averages for seven rotors tested. Rotor resistance losses are the key item in rotor material substitution and yielded a 40% reduction in measured losses. This represents 80% of the theoretical maximum value possible in the conductivity difference between rotor materials. This is a very good start for a first attempt at real motors and may be improved further with detail lamination slot design.

Table I – IEEE Loss Segregation Results for 15 Hp (11.2 kW) Motor

	Al (W)	Cu (W)	ΔW	%
Stator Resistance	507	507	0	0
Iron Core Loss	286	286	0	0
Rotor Resistance	261	157	-104	-40
Windage & Friction	115	72	-43	-37
Stray Load Losses	137	105	-32	-23
Totals	1306	1127	-179	-14

Windage and friction losses are mechanical losses retarding rotation. Although these seem to have no relevance to rotor material, they do in this case. The copper rotors cast had smooth end rings except for projections for balancing weights. Cooling fins were not cast on to the end rings. With a lower resistance rotor, less heat is generated to be dissipated. These rotors, lacking fins, were adjoined on the shaft with an internal circulating fan for stator cooling. These fans are more efficient as they can be sized for their circulating job with less rotor heat to dissipate. As a result, when compared to aluminum rotors with fins, total windage losses were down 37% from 115 watts to 72 watts. Friction in the bearings is assumed to be the same. An added advantage of the small adjoined fan is that less copper is used and weight is reduced by eliminating the rotor end ring fins.

Stray load losses are the cumulative effect of magnetic transfer efficiency between the stationary stator and the rotating rotor as experienced in the air gap between the two. Consistent air gap and rotor balance also affect stray load losses and there is an electrical component to the magnetic transfer efficiency. Consistency in conductivity of rotor conduction bars is critical to proper induction magnetic transfer. Porosity or nonmetallic inclusions in cast rotor bars can result in variation in effective rotor bar cross sectional area, and therefore resistance, and variation in the magnetic field in the air gap. This increases stray load losses via inconsistent magnetic flux density between stator and rotor reducing overall efficiency. The seven copper rotors exhibited such rotor bar consistency so as to reduce stray load losses by 23%, from 137 watts to 105 watts. It is clear that the die-cast copper rotors contributed to the overall motor efficiency via a consistency not normally achieved in typical aluminum rotor motor production.

The substitution of copper as rotor material directly achieved 58% of the total savings and was materially involved in saving the other 24% in windage losses and 18% in casting accuracy stray load losses. The combination resulted in 179 watts of savings or a total of 14% reduction in total losses. These results support the efficacy of both the material and the process. The rotors required only touch up balancing instead of the weights usually used to compensate for nonuniform rotor weight distribution due to casting porosity.

Other Performance Measures

In addition to the loss measurements, the test method itemizes performance issues such as temperature rise above ambient, full load speed and power factor (Table II). These data reveal a motor having different characteristics than a typical aluminum rotor motor. Overall efficiency resulted in a solid addition of 1.2 percentage points added directly to the motor nameplate efficiency. This is significant in that 20 years of motor efficiency improvements have already utilized all of the easy things that reduce losses. Copper rotors represent one of the largest possible reductions in losses without using amorphous steels or superconducting windings, still exotic and very expensive alternatives.

Table II – Performance Characteristics of 15 Hp (11.2 kW) Motor

	Al	Cu	Difference	% Change
Efficiency	89.5	90.7	+1.2	+1.4
Temperature Rise, °C	64.0	59.5	-4.5	-7.0
Full Load RPM	1760	1775	+15	+0.85
Slip, %	2.22	1.37	-0.85	-38
Power Factor, %	81.5	79.0	-2.5	-3

Temperature rise above ambient is significant in the life expectancy of the motor. The general rule of thumb in the motor industry is that for every 10 degrees Centigrade hotter a motor runs, life expectancy can be cut in half. With nearly 5°C reduction in the copper motor temperature rise, we can expect a possible 50% increase in motor life when the motor is operated near design capacity. Only real field tests and time would be able to prove this hypothesis, but similar results have appeared in premium efficiency motors. Power factor is down slightly (3%) but is very near measurement accuracy levels. Power factor is only an issue if the electric power utility measures a low power factor for the entire factory facility.

Slip is the difference between the synchronous RPM of the field rotation at 60 Hz (or 50 Hz elsewhere in the world) and the full load RPM of the rotor and shaft assembly. This difference is what creates the torque to rotate the load. The copper rotors achieve this torque point with less slip or a higher measured RPM. Starting, breakdown and locked rotor torque values are somewhat reduced in the copper rotor motor. Since we have simply substituted copper for aluminum with no design change to accommodate the copper, these torque factors could be corrected with changes in the cross sectional shape of the rotor bars not necessarily requiring an increase in total copper cross sectional area and cost.

Other Motors Tested

In a larger 25 Hp (18.5 kW) motor, the end rings were 6.5 inches (165 mm) in diameter with a stack height of 9.5 inches (241 mm). The squirrel cage contained 11.4 kg of copper and required melting 17.7 kg of copper per shot. The motor manufacturer provided sufficient laminations for 14 rotors. Motor tests of this second set of larger rotors showed even more dramatic results. This in part is due to the use of a rotor lamination slot design specifically designed for copper.

Again there was remarkable consistency in the results for the four rotors tested and compared to the same motor with an aluminum rotor. The rotor losses were 40% lower in the copper rotors and the overall losses were reduced by 17.6%. When the stator was optimized for the copper rotor, overall losses were reduced by 23%. Lower losses led to reduced rotor and stator temperatures. On completion of tests, the temperature of the stator winding of the motor with the copper rotor was 32°C cooler than that of the aluminum design; the copper rotor was 29°C cooler than the aluminum rotor. Lower running temperatures mean that smaller internal cooling fans can be used and this had a significant effect in reducing the parasitic component of the friction and windage losses on this motor designed for the copper rotor. Motor temperature translates directly to motor life and maintenance costs. Motors with cast copper rotors, with proper maintenance, would be expected to last longer and be more reliable.

A set of rotors cast for another motor company were for a 4 Hp (3 kW) motor. The end ring was 3.54 inches (90 mm) in diameter, stack height 6.1 inches (155 mm) and contained 3.2 kg of copper. Overall motor losses were reduced by 21% with the copper rotor compared to the conventional aluminum.

Copper rotors for a 5 Hp (3.7 kW) motor were cast for a fourth manufacturer. Rotor I^2R losses were reduced by 38% compared to the aluminum counterpart motor, but surprisingly, the iron core loss component was much higher for the motor with the copper rotor. This was apparently due to insufficient consideration of the rotor and stator lamination designs from the aluminum rotor motor used. It appears the iron was almost totally saturated in the aluminum design. The higher current in the copper rotor could not further magnetize the iron and appeared as a large apparent loss.

As shown in Table III, I^2R losses for all motors fitted with copper rotors from this test program showed rotor reductions of about 40% with one smaller motor showing an even greater reduction.

Table III – Rotor I^2R Losses – Copper vs. Aluminum

HP	kW	Poles	Al	Cu	Difference	%
4	3	4	221	92	129	-58
5	3.7	4	--*	--*	--*	-38
15	11	4	262	157	104	-40
25	19	4	410	292	118	-40

*Actual loss values not reported

Metallurgical examination of cast copper rotors confirmed that there was no interaction between the copper conductor bars and iron laminations. Chemical analysis revealed that small amounts of iron (10 to 11 ppm) and oxygen (0.084 to 0.163 wt. %) were picked up during casting. The combined effects of the presence of microstructural defects and chemical contamination reduced the electrical conductivity of the cast copper conductor bars only slightly to 96.8% and 98.7% IACS in the two measurements performed on the first set of rotors cast.

Porosity in the far end ring of the first set of copper rotors appeared to be 2 to 3 percent but did not extend into the conductor bars. The uniformity of conduction paths in these copper rotors shows up as a reduction in stray load losses and had not been expected. No balancing to compensate for uneven weight distribution was required. The larger rotors of the second group cast were more of a problem in this regard showing as much as 25% voids in the first shots and 8 to 10% in the rotors tested for electrical performance. Ongoing studies have shown that porosity in the far end ring can be greatly reduced by using the real-time shot control cabability of the die casting machine to fill the die to a point beyond the gates prior to accelerating the ram. Gas in the melt from the long unprotected melt time (about 13 min because of the small power supply available) could also contribute to rotor porosity. In any event, porosity was confined to the end rings, was apparently evenly distributed and had little apparent effect on the performance of these copper rotors. Die cast aluminum rotors very often have considerable porosity requiring use of extra aluminum to compensate for porosity and always require balancing.

Copper Rotor Literature Data

Table IV summarizes the overall motor efficiencies and loss reductions observed in motors fitted with copper rotors where comparisons with aluminum are reported in the literature including the data of this study. A broad range of motor power from 4 Hp (3 kW) to 270 Hp (200 kW) is covered. A clear pattern of increased efficiencies with higher values for the larger motors and loss reductions due to substituting copper for aluminum in the rotor averaging 14.7% is evident.

Table IV – Overall motor Efficiencies and Loss Reductions via Copper Rotors
Data from this Study and the Literature

Hp	kW	Poles	Eff. Al	Eff. Cu	Diff.	Loss Reduction, %	Reference
4	3	4	83.2	86.4	3.2	19.0	This study
7.5	5.5	4	74.0	79.0	5.0	19.2	5
10	7.5	4	85.0	86.5	1.5	10.0	6
15	11.2	4	89.5	90.7	1.2	11.4	This study
25	18.8	4	90.9	92.5	1.6	17.6	This study
40	30	4	88.8	90.1	1.3	11.6	7
120	90	2	91.4	92.8	1.4	16.3	7
270	200	4	92.0	93.0	1.0	12.5	5

CONCLUSIONS

The motor performance tests reported here have verified years of calculations on the part of motor manufacturers about the prospective benefits of incorporating copper in the squirrel cage structure. The results show conclusively that overall motor energy losses are reduced by an average 14% and the nameplate efficiency is increased by at least a full percentage point. Copper rotor die castings were of high quality and had no significant porosity in the conductor bars. Extended production runs will be required to prove the point, but these tests show promise that the INCONEL alloys 617 and 625 operated in the 600-650°C (1112-1202°F) temperature range are very promising die materials for die casting of copper motor rotors.

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