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Copper in the Rotor for Lighter, Longer Lasting Motors

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Abstract

This paper reviews the advantages of substituting die-cast copper for aluminum in the motor rotor. This advance in motor technology has been long sought by the motor industry but short die life due to the high melting point of copper frustrated attempts to manufacture by pressure die casting. The nickel-base alloy hot die technology developed to solve the manufacturing problem is briefly reviewed. Development work done prior to the present program and commercial motors derived from that work have focused on the increased electrical energy efficiency achievable by using copper with its higher electrical conductivity in the rotor. Performance characteristics of example industrial motors are presented. Modification of the conductor bar shape to control in-rush current and starting torque to accommodate copper in the rotor will be discussed. Modeling by motor manufacturers has shown that by using copper in the rotor, a lighter motor than an aluminum rotor motor at the same efficiency can be built. An example of weight savings calculated for a 15 Hp (11 kW) motor is presented. Data presented here show that motors with copper rotors run cooler. Industry experience shows that cooler operation translates to reduced maintenance costs, improved reliability and longer motor life.

Introduction

The Defense community needs are being driven by the need for lighter weight, lower cost, environmentally friendly, and more reliable materials for the Objective Force. Reduced weight is a goal for all weapon systems and logistics support items. The Copper-Based Casting Technology (C-BCT) program supports these goals. The objectives of the C-BCT program are to develop, demonstrate, and deploy applications of copper base alloys to make significantly lighter, more efficient, components for use in defense systems. Specifically, the program will build on new and successfully demonstrated tooling technology to develop and test electrical motors that utilize die-cast copper in the rotor squirrel cage structure. These motors will weigh less, last longer, and operate more efficiently than currently available motors.

CBC-T is a four-year funded program comprised of government, industry, and academic team members. The team includes two motor manufactures addressing military, industrial, and aerospace motor applications; an advanced casting and manufacturing facility; a leader in analysis and testing for power electronic and electromechanical systems; a leading research institution in the area of materials characterization; as well as representatives from the Army Research Lab (ARL), and the Defense Logistics Agency (DLA).

The program seeks to design, build and test die-cast copper rotor motors having improved electrical energy efficiency or having a substantial weight advantage compared to the aluminum counterpart. Experience has shown that high efficiency motors with copper in the rotor operate at lower operating temperatures compared to the equivalent aluminum rotor. Maintenance costs and the frequency of replacement are directly related to operating temperature. Both 60 Hz motors for ship board and 400 Hz motors for aircraft application having these advantages are included in this project.

Because the electrical conductivity of copper is nearly 60% higher than that of aluminum, one would expect the I^2R losses in the rotor to be substantially lower if copper were substituted for aluminum as the conductive material of the squirrel cage structure. Motor modeling by several manufacturers has shown that motors with copper-containing rotors would have overall loss reductions of 15 to 20%. Aluminum has been the material of choice for all but very large motors because the intricate squirrel cage is readily manufactured by pressure die casting through the rotor lamination stack. The large motors (>250 Hp, 200 kW) and a few smaller special purpose motors with copper in the rotors are assembled by a slow and costly fabrication technique that is not economical for production of the millions of integral and fractional horsepower motors sold annually. Die casting of the copper will be required for rapid and cost-effective manufacture, but the process has not been practical because of short die life resulting from the high melting temperature of copper.

There were two phases to the work described in this paper. The first phase addressed the problem of die life in pressure die casting copper by surveying a number of candidate high temperature die materials and the optimum conditions for their use to maximize die life. The significant results of the die material study are briefly summarized here; more complete accounts have been published elsewhere [1], [2]. In the second phase, copper rotors were die cast for several major motor manufacturers for evaluation by dynamometer testing in their own facilities. This paper presents these data on performance of motors incorporating the die-cast copper rotors and compares the performance to that of the same motor with an aluminum rotor. Motor performance data from companies that have or are about to offer copper rotors for sale are also presented. Comparison of the cost and weight of copper motors now available commercially compared to the costs and weights of aluminum rotor motors at the same 1997 Energy Policy Act (EPAct) efficiency determined by a modeling exercise has shown that in many cases the copper motor can actually be built less expensively.

Use of copper in the rotors in a broad range of sizes of induction motors could represent 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. The nameplate efficiency of a typical in-service 15 Hp (11 kW) 1800 rpm motor today is about 89.5%, still below the EPAct standard of 91%. As shown by the test results presented here, adoption of the copper rotor should bring efficiencies to the 94 to 96% range exceeding the requirements of today's premium efficiency motor, nominally 93%. There are few material and engineering options to reach higher efficiency short of suffering greatly increased costs by employing amorphous iron alloy laminations or superconductivity.

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 both industrial and defense systems.

The potential energy savings achievable through the use of copper rotors is substantial. The U.S. Department of Energy reports that motors above 1/6 Hp use about 60% of all electricity generated in the United States and that medium power motors (1 to 125 Hp), the most likely candidates for conversion to copper rotors, use about 60% of the electricity supplied to all motors [3]. In the U.S. alone, a one percentage point increase in motor electrical energy efficiency would save 20 billion kW-hrs or $1.4 billion (at 7 cents per kW-hr) and 3.5 million barrels of oil annually.

Die Technology for Cost Effective Die Casting of Pure Copper

Although motor manufacturers have long recognized the value of using electrical grade copper in the rotor, the poor manufacturing economics of die casting copper has been an impenetrable barrier. The high melting point of copper (1982°F, 1083°C) results in very rapid deterioration of tool steel dies. The principle failure mechanism is referred to as "heat checking" by die casters, but decarburization and softening of the steel at the high surface temperature are also contributors. Heat checking is a thermal fatigue phenomenon resulting from the rapid cyclic expansion of the die surface layer on contact with molten metal and the constraint of the surface by the much cooler inner portions of the die. Cooling of the outer layer on each cycle to a temperature below that of the bulk of the die puts the surface under a large tensile stress that can exceed the yield point of the die material. This surface-to-interior differential expansion and contraction is greatly exacerbated in die casting high-melting metals such as pure copper. Clearly much improved die life had to be achieved for the copper rotor to be practical. Therefore it was necessary to identify suitable high temperature die materials and a test program for this purpose was conducted.

3-D thermal modeling of die thermal profiles provided considerable insight into the heat checking failure mechanism and how to prevent or minimize it. The modeling studies demonstrated that the surface-to-interior ΔT and resulting large strains could be minimized by raising the temperature of the bulk of the die insert. It was shown that in the cases of molybdenum- or tungsten-base die inserts, preheating and operation of the die at 550ºC or slightly higher would reduce cyclic strains on the surface to below the plastic range. Because of the lower thermal conductivity of nickel base alloys, the minimum operating temperature was determined to be 625ºC. Devising and demonstrating a practical system for heating and insulating the die inserts to maintain the high temperature critical to improving die life became an important objective of the research.

The test dies, copper melting process and die heating technology used in the die material study and now finding commercial application are described in detail elsewhere (Peters et al 2002). To obtain the high die insert temperatures indicated in the die thermal study, the arrangement of electrical resistance heaters and die insert insulation shown schematically in Figure. 1 was designed and built.

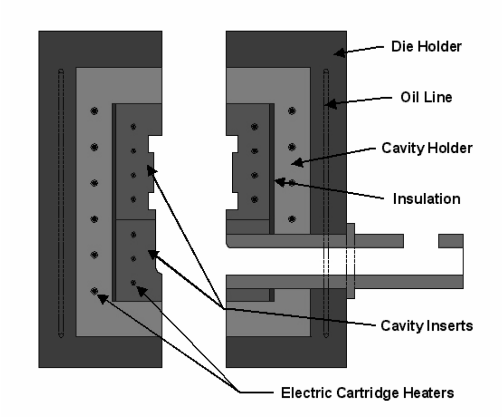

Figure 1. Schematic illustration of the placement of electric resistance heaters and insulation in the die material testing and now being adopted commercially by motor manufacturers

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In the die material test conducted, as expected, the H-13 inserts showed distinct heat checking after only 20 shots of molten copper. More serious cracking was generated on subsequent shots. Several high temperature materials were then tested. The molybdenum alloy TZM and the tungsten alloy Anviloy, when operated at 550°C or slightly above appeared to be capable of extended runs in this severe copper die casting exercise. The TZM alloy is however subject to severe oxidation at copper casting temperatures and would not be suitable unless appropriately coated to provide protection. A number of nickel base alloys were then evaluated because of their generally excellent combination of high temperature strength and oxidation resistance. These nickel base alloys were of very different types including solid solution strengthened INCONEL alloy 617, gamma prime strengthened INCONEL alloy 718 and the mechanically alloyed dispersion strengthened INCONEL alloy 754. The simple solid solution strengthened type proved to resist heat checking for several hundred shots when operated in the temperature range 625 to 640ºC (1175 to 1187ºF).

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. Although not tested in this study, another similar nickel-base alloy, 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 is in use in the first copper rotor production die set now in operation. An important conclusion from this research is that it is absolutely essential to operate the dies 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 (1202°F) are not required and in fact would reduce productivity by increasing cooling time. The copper die castings were found to have a sound structure and only small well distributed shrinkage voids. Chemical analyses showed iron, nickel and oxygen pickup to be minimal. Electrical conductivity of these castings averaged no lower than 98% IACS. A practical die heating and insulation design has been developed.

Motor Performance Test Results

A sizeable body of data on the performance of motors with copper rotors has now been generated. A total of about 140 rotors were cast for four motor manufacturers to evaluate in their own laboratories in the CDA program. These were for the most part a direct substitute of copper for the aluminum with no changes to the rotor slot pattern or other motor design modifications to better utilize the high electrical conductivity of copper. One motor from this group is described here in some detail. More recently, performance data generated by SEW Eurodrive in Germany have been reported to CDA. The copper rotors for these motors were die cast in Europe. The SEW motors have been optimized for copper and give us insight into the potential for weight and cost saving in using copper in the rotor and for this reason are detailed here. Results from this large body of work are summarized in this section to show the substantial improvement in electrical energy efficiency resulting from the use of copper in the rotor rather than aluminum and to provide the reader with a feeling for the difference in motor characteristics (torque, speed, temperature rise) effected by utilizing copper in the rotor.

Motor performance data were obtained by dynamometer efficiency tests as per IEEE Specification 112, Test Method B, as required in the U.S. by the National Electrical Manufacturers Association (NEMA). One European 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:

Iron Core Losses – magnetic losses in laminations, inductance and eddy current losses.
Stator Resistance – current losses in the windings.
Rotor Resistance – current losses in the rotor bars and end rings.
Windage and Friction – mechanical drag in bearings and cooling fan.
Stray Load Losses – magnetic transfer loss in the air gap between stator and rotor.

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, and with one exception, requested that they not be identified.

15 Hp (11.2 kW) Motor Test Results: This motor tested by a U.S. motor manufacturer yielded a good deal of data and a particularly thorough analysis of the results. The copper rotors for a 15 Hp (11.2 kW) motor and were 5.7 inches (144.8 mm) in diameter with a 6-inch (152 mm) stack height containing 14 lbs (6.4 kg) of copper in the conductor bars and end rings. 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.

Seven rotors covering process variables were tested and compared to a large database of similar aluminum rotor motors averaged as a "typical" motor. Since the same "standard" stator was tested seven times, the spread of test results ranged from 502 watts loss to 522 watts loss. This represents an approximate plus or minus 2% testing error which has to be assumed across all test data. As a result, 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.

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 loss. With only seven tests, no pattern could be discerned relative to any of the process variables; pressure, stroke or quench. The consensus conclusion is that the process is very robust and process variations within the range tested have no predictable effect on final performance results.

From the remarkable consistency of the test results, it is concluded that the casting process is viable and robust. Results variations are all within test measurement accuracy and no pattern emerged in the variables. When compared to historical variation in aluminum rotor motors, these copper rotors were so consistent as to deem the data variation insignificant.

Table 1 shows the IEEE test results as averages for seven rotors tested.

TABLE 1
IEEE LOSS SEGREGATION TEST RESULTS
FOR A 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

Rotor resistance losses (I^2R) 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. 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. They did not include cooling fins on the end rings that both dissipate rotor heat and circulate internal motor air to even out hot spots in the stator windings. 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 need to dissipate rotor heat. As a result, when compared to aluminum rotors with fins, total windage loses were down 37% from 115 watts to 72 watts. Friction in the bearings is assumed to be the same. The cooler running copper rotors allow reduced windage losses via a more efficient internal fan and reduce the amount of copper required 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. Although this can be affected by consistent air gap and rotor balance, there is also an electrical component to the magnetic transfer efficiency. Consistency in rotor conduction bars is critical to proper induction magnetic transfer. Porosity or nonmetallic inclusions in these cast rotor bars can effectively change the "wire gauge" of the bars from one bar to another. Variation in rotor bar cross sectional area, and therefore resistance, causes 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. A more accurate and consistent casting process might possibly produce similar stay load improvements in aluminum rotors. It is clear that the copper rotors cast using the heated nickel alloy casting process developed in this project contributed to the overall motor efficiency via a consistency not normally achieved in typical 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 did not even require balancing weights that are usually used to compensate for rotor bar inconsistencies.

Performance characteristics of this motor are shown in Table 2. Overall efficiency resulted in a solid addition of 1.2 percentage points added directly to the motor nameplate efficiency. As noted above, this is significant in that 20 years of motor efficiency improvements have already utilized all of the easy things that reduce losses.

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.

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. It adds a low power factor penalty to the electric bill to pay for correction capacitors added to the utility yard to compensate for the phase shift. Most customers do not have this penalty but if they do, it is the entire facility that is corrected, not each individual motor.

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. This creates what is called in the industry a "stiff" motor or one that does not slow down much under load. This implies a very responsive motor on variable frequency drives if high performance servo-like speed changes are desired. It does, however, also imply potential problems on

TABLE 2
PERFORMANCE CHARACTERISTICS
OF THE 15 HP (11.2 KW) MOTOR

	Al	Cu	Difference	% Change
Efficiency	89.5	90.7	-1.2	+1.4
Temp. Rise, ºC	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

variable torque loads like fans and pumps. These applications are subject to the Cube Law of energy input since it varies with the cube of the speed change. With a 1% increase in full load speed, the energy used on these applications will go up by the cube, or 3%, because of the higher speed. They are moving more air or water but it appears that energy usage has gone up despite a more efficient motor. This can cause problems in application as experienced in past improvements from standard motors to premium efficiency which produced similar increases in full load RPM amp draw. This is solvable in proper application engineering by simple adjustment in pulley ratios to bring the fan back down to its design speed.

With the rotor laminations designed for aluminum used in these test rotors, torque is down, but this problem is solvable. The production motors that the copper rotors were compared to are historically very high torque motors well above NEMA required minimum levels. The copper rotors exhibited a significant drop in each of the torque measurements but only from an historical high level to near NEMA minimum levels. A certain amount of this is expected from a higher conductivity rotor. Normal motor design utilizes a variety of aluminum alloys with different resistances to achieve different torque characteristics. High resistance aluminum allows higher slip and therefore higher torques. As shown in Table 3, these copper rotors with higher conductivity and lower slip did not produce the same torques.

TABLE 3
MEASURED TORQUE VALUES IN LB-FT FOR THE
15 HP (11.2 KW) MOTOR

	Al	Cu	Difference	%
Starting Torque	58.2	37.0	-21.2	-36
Breakdown Torque	152.0	125.9	-26.1	-17
Locked Rotor Torque	69.0	65.0	-4.0	-6

Locked rotor torque is the static measurement and the copper rotors performed very close to normal motor expectations. Dynamic performance of starting torque to get the load up and running is the most alarming at over 1/3 reduction. This could imply problems on high inertia loads. Breakdown torque (how much load will stop a running motor) is also down 17% but still within NEMA minimums and down only from already very high levels in the data base. With further design adjustments we surmise that 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.

These test data do not give all that is necessary to do a complete economic analysis, but a number of important implications can be drawn. A total drop of 179 watts implies a nearly 1600 kilowatt-hour reduction in energy use per year on continuous duty or over $100 per year savings at typical industrial electric rates in this 15 Hp (11.2 kW) motor. This adds measurably in the life-cycle costing over a typical 10-year life span and even more if the life is extended due to the lower temperature rise. Moreover, there is another significant factor in that this "optimized"' copper rotor design was only a 6-inch (152.4mm) stack of lamination material as opposed to a standard EPAct aluminum rotor stack length of 6.5 inches (165.1mm) in Open Drip Proof motors and 7.5 inches (190.5 mm) in Totally Enclosed Fan Cooled motors. This implies savings of 0.5 to 1.5 inches (12.7 to 38.1 mm) of both rotor and stator core iron as well as the stator windings and rotor conductive material. These weight and cost savings have the potential to at least offset, and in some cases, exceed the increased cost and weight of the die-cast copper rotor.

Industrial Motors Expressly Designed to Use Copper in the Rotor

The copper rotor motor described in the preceeding section and a number of other motors built and characterized in this project (Cowie et al 2003, Brush et al 2004) were all simple substitutions of copper for aluminum in the rotor with no design modifications to take maximum advantage of the higher electrical conductivity of copper. SEW-Eurodrive has been active in an extended effort to increase the efficiency of their entire line of industrial motor drive systems. Increasing the electrical energy efficiency of the motor was necessarily an important part of this effort. Preliminary work had shown that as expected, increased motor efficiency could be obtained by using copper in the rotor and it appeared that the efficiency increases could be obtained without an increase in motor size as would be necessary with an aluminum rotor. SEW then undertook a program to design the motor to optimally use copper in the rotor. In April 2003, this company announced the availability of a range of motors meeting EPAct and European EFF1 efficiency standards. High efficiency die-cast copper rotor motors to 60 Hp (45 kW) are now available. The higher efficiency has been obtained in large part by employing electrical grade copper in the rotor although rotor and stator lamination and winding designs were also modified.. These modifications succeeded in raising efficiency over the entire load spectrum while at the same time maintain torque at critical points on the torque-load curve including starting torque. This section presents the major design considerations and results of motor performance tests by IEEE standard 112B for 1.1, 5.5, 11 and 37 kW (1.5, 7.3, 15 and 50 Hp) motors at both 50 and 60 Hz.

Table I presents efficiency data for all four SEW aluminum and copper rotor motors. Comparison of these motors is especially interesting because two different design concepts have been employed for the small and larger copper motors. The 1.1 kW motors essentially have the same layout of stator and rotor laminations; i.e. the aluminum rotor bars have simply been replaced by the die-cast copper. But the lamination steel has been upgraded from material with losses of 8 W/kg to a better grade with losses rated at4 W/kg. In contrast, the high efficiency larger motors have a completely new lamination and stator design. The design modifications relate to the starting behavior discussed below. The data in Table 4 show that the copper rotor leads to a significant increase in efficiency while maintaining the outer motor dimensions standard for aluminum – regardless of design.

Table 4
Full-Load Efficiencies by IEEE 112-B
for the New High Efficiency Copper Rotor Motor Series
and Standard Efficiency Aluminum Rotor Series

Power Rating	Copper Rotor	Aluminium Rotor
1.1 kW	84.1 %	77.4 %
5.5 kW	89.7 %	86.6 %
11 kW	91.1 %	89.4 %
37 kW	93 %	90.4 %

To evaluate the efficiency contribution of the copper rotor, Figure 2 shows the loss distribution data for all four motors. Here the losses measured for the high efficiency copper rotor versions are compared to the standard aluminum rotor designs. These figures clearly show that the main effects arise from reduced rotor losses. Because of the diagram scaling, the effect for 1.1 kW does not show clearly, but indeed a reduction of rotor losses from 39 W to 27 W was observed which is a drop of more than 30%. Since lower losses also lead to decreased operating temperatures, stator copper losses are also reduced.

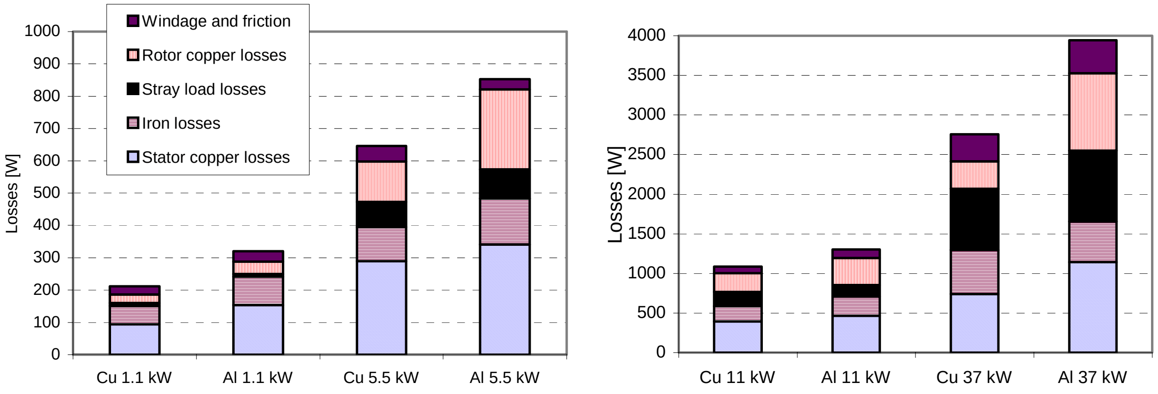

Figure 2. Loss distributions at 60 Hz for the four SEW motors, copper rotor versions compared to the aluminum rotor lower efficiency standard line.

A loss component which becomes increasingly important with increasing power ratings are stray load losses (SLL). In Figure 3 these losses for the motors of this study are compared. Generally it has been observed that, in direct substitution of copper for aluminum in the rotor, the copper motors have lower SLL than their aluminum counterparts. In this situation where redesign has introduced a number of changes that could affect the SLL, there are both increases and decreases in changing from aluminum to copper. But no large increase in SLL due to copper is observed and the SLL losses are no more than 2% of the input power.

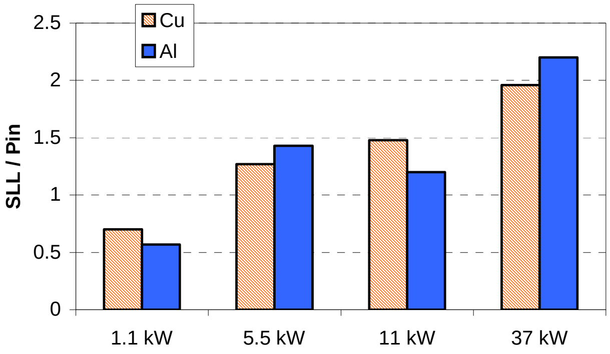

Figure 3. Stray load losses per unit input power for the four SEW motors sizes.

In industrial applications, it is quite common that drives do not run at full load at all times. Full load efficiencies are important, but partial load efficiencies must also be taken into account. For that reason Figure 4 shows the dependence of efficiency on output power.

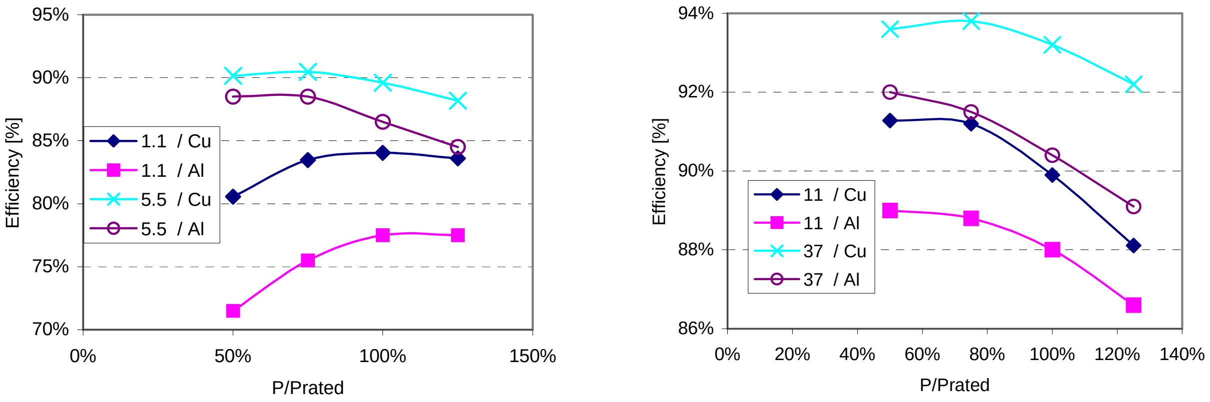

Figure 4. Efficiency dependence on out put power at 60 Hz.

Even in the partial load regime the efficiency of the copper rotor motors stays above the corresponding standard efficiency aluminum motors. On the other hand, the efficiency drop for output powers greater than 100% is smaller than it is for aluminum motors except in the 11 kW motor where the efficiency at partial loads is quite a bit higher in the copper rotor motor. The smaller drop in efficiency in the overload region is due to the lower temperature rise of the high efficiency motor and therefore these motors have more thermal reserves which support good overload capabilities.

If aluminum bars are simply substituted by copper as in the 1.1 kW motor example mentioned above, the breakdown slip s_k becomes lower since $s_k \sim R_2$. Focusing on starting conditions, this approach leads to decreased starting torque and higher starting current. In Figure 5 (left), torque-speed and current-speed curves for both 1.1-kW motors are compared. The starting torque of the copper motor is 15% below that of the aluminum motor but well above two times rated torque. On the other hand, starting current is increased by about 30%. But the absolute numbers are still controllable and far from being critical in this smaller motor. For that reason only minor design changes had been necessary for 1.1 kW motor.

The situation is different for motors of higher power rating where starting currents become more critical. Therefore a completely new lamination design was developed for all SEW high efficiency motors above 3 kW. The curves in Figure 5 (right) display the results for the 5.5 kW motor. Again the R_2 effect with lower breakdown slip and steeper torque curves is obvious. But comparing the starting conditions, currents are nearly the same, despite the lower rotor bar resistance. On other hand the starting torque is approximately 20% lower but this was indeed a desired effect, since lower, but sufficient starting torque is beneficial for gear box life.

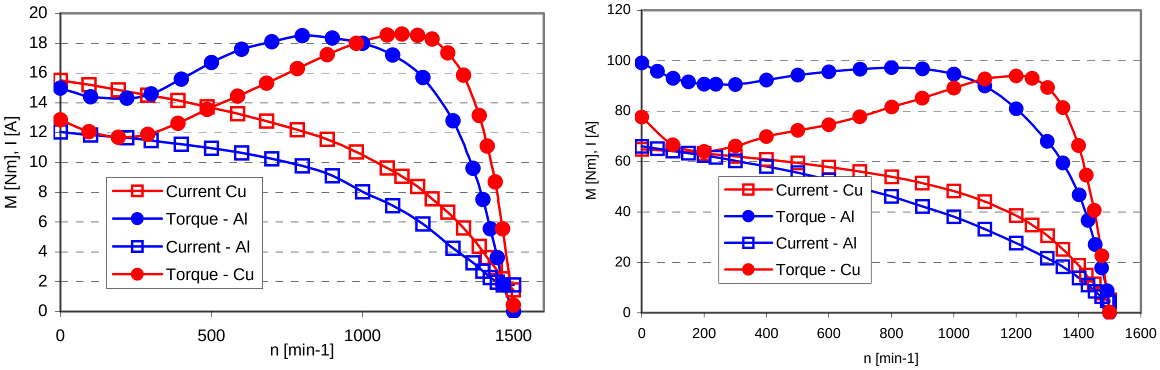

Figure 5. Torque-speed and current-speed curves for1.1 kW motors (left) and 5.5 kW motors (right). Standard efficiency Al motor (blue); Cu high effficiency motor (red).

It is interesting to note that in taking the decision to use copper in the rotor for this series of industrial drive motors to reach EPAct and EFF1 minimum efficiencies, SEW conducted an extensive modeling study comparing the size, weight and overall costs of motors of equivalent efficiency using aluminum in the rotor. The finding was that, for the motors discussed here, the use of copper in the rotor cage allowed reductions in rotor diameter, in iron required for laminations and in stator copper windings. The copper rotor motors are one frame size smaller than the the aluminum rotor design would have allowed. This was particularly important to this manufacturer because the smaller high efficiency copper rotor motor allowed use of the same gear box obviating the need to replace this in the entire product line. Overall there was an accompanying reduction in total manufacturing costs; the cost of the motor with an aluminum rotor at a given EFF1 efficiency ranged from similar to 15% higher than the copper version. In these examples, weight savings of up to 18% and cost savings of up to 15% were effected. This cost saving for the copper rotor motor was in spite of the copper rotor die-casting component of the total costs being typically three times more costly than the aluminum rotor.

Analysis by U.S. manufacturers of 7.5 and 15 Hp motors and assembled by CDA as a composite equivalent U.S. motor meeting EPAct efficiency standards came to similar conclusions. The die-cast copper rotor motors would be 18 to 20% lighter and 14 to 18% less expensive to build than the aluminum rotor motor at the same efficiency when a frame size reduction was possible. When a frame size reduction was not possible, reductions and weight and cost were still indicated in the design studies, but the percentage reductions were in the single digits for the copper rotor machine.

Optimizing Rotor Design for Copper

As noted, much of the data in the literature on motor tests to characterize performance of copper rotors have been done with rotor laminations and slot designs designed for aluminum rotors then in production. While this straight forward substitution of copper for aluminum showed very substantial reduction in losses and increases in motor efficiency, designing the motor as a whole and the shape of the rotor bars in particular for the high conductivity of the copper in the squirrel cage would be expected to further enhance motor performance. A useful understanding of how different slot shapes work has been developed through the use of frequency response curves that describe slot impedance as a function of rotor frequency (Kirtley 2004).

Using a simple induction motor model equivalent circuit, torque-speed curves have been generated. The shape of these curves is quite sensitive to the rotor equivalent resistance R_2 which is in turn inversely proportional to the conductivity of the conductor bar material and cross sectional area. Taking into account the smaller skin depth and paying attention to the stray load loss contributions resulting from harmonic frequencies, it has been shown that a slot shape having a starting bar connected to the rest of the bar (the running bar) is the general approach to optimizing the slot shape for copper in the rotor. The conventional bar shape used in an aluminum rotor and the general copper bar shape are shown in Figure 6. This optimization process continues.

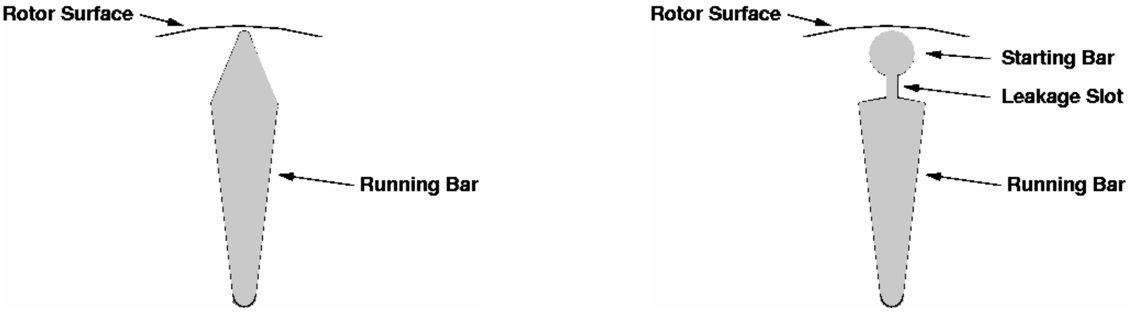

Figure 6. Aluminum conductor bar left and copper bar right

Conclusions

In a cooperative effort of the U. S. and world copper industries and a number of major motor manufacturers world wide, real progress has been made in the long sought goal of improving the induction motor by substituting die-cast copper for aluminum in the rotor. Manufacturing obstacles to production of copper rotors associated with very poor die life in the copper die casting operation have been solved with development of a heated nickel-base alloy die system. This system has demonstrated die life increase of 50 to 100 times compared to tool steel dies and is now in commercial use producing copper rotors. As predicted by motor manufacturer modeling and prototype studies over the years, rotor I^2R losses are reduced by about 40% when copper is substituted for aluminum in the rotor squirrel cage structure. This reduction is an important contributor to substantial increases in overall electrical energy efficienciy of the motors discussed in this paper. Reductions in stator, iron and stray load losses are seen as well. A very important side benefit of higher efficiency is the resulting reduced temperature of operation. A rule of thumb of motor designers is that motor life doubles with each 10 degree C reduction in operating temperature. It is expected that copper rotor motors replacing large numbers of conventional motors in legacy weapons systems by the Defense Logistics Agency will last at least 50% longer. Defense Supply Center Richmond alone buys $32 million in replacement motors each year. Over a period of years, this reliability increase will eventually save DSCR at least $8 miillion per year in current dollars.

The copper rotor offers defense systems other potential benefits where weight savings or a smaller motor would have advavtages. Motor manufacturer design studies on optimum copper rotor motors have shown that in many instances the copper rotor allows a smaller diameter rotor and reductions in the rotor and stator iron, and stator windings compared to achieving the same efficiency objective with an aluminum rotor.

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