Performance of Motors with Die-cast Copper Rotors in Industrial and Agricultural Pumping Applications

D. T. Peters and J. G. Cowie
Copper Development Association Inc.
260 Madison Avenue
New York, NY 10016

E. F. Brush, Jr.
BBF Associates
68 Gun Club Lane
Weston, MA 02193

M. Doppelbauer and R. Kimmich
SEW Eurodrive GmbH & Co. KG
Ernst-Blickle Str. 42
D-76646 Bruchsal, Germany

Abstract - **This paper adds to the growing body of data showing improved efficiency and cooler running temperatures for copper rotor motors. Test data for motors where copper has simply been substituted for aluminum with no change in design are presented for a series of motors built in India for pumping water for agriculture and two industrial motors are described. Design modifications to better utilize copper in the rotor and resulting motor performance for two other industrial motors are then reported.**

I. Introduction

A considerable literature has been published in the past few years on the benefits to the performance of the induction motor by using copper as the conductive material in the rotor [1], [2], [3], [4,]. These papers consistently show that the higher electrical conductivity of copper compared to aluminum results in higher electrical energy efficiency of the machine by reduction in rotor I^2R losses and often through reduced stray load and windage and friction losses as well. The more efficient machine necessarily has lower slip and thus runs at a slightly higher speed. These higher efficiency motors often have comparable or somewhat higher breakdown torque compared to the aluminum rotor counterpart, but when copper is simply substituted for aluminum, starting or locked rotor torque is reduced and starting currents are higher. This can be a problem in many applications.

Recently, efforts to improve the starting characteristics of the motor and to generally accommodate the design to better utilize the high conductivity copper in the squirrel cage have been undertaken [5]. Two industrial motors are reported on here where changes to the rotor slot shape, in one case with changes to the stator design, and in the other with no change to the stator, markedly change motor performance. A third smaller motor with copper directly substituted for aluminum using the same rotor laminations is also described. Another set of motors produced in India for water pumping in agriculture use copper in the rotor by simple substitution for the aluminum. Motor performance from both laboratory tests and in-field pumping are presented.

The benefits of the copper rotor have long been appreciated by the motor community but manufacturing difficulties in producing large numbers of integral horsepower motors in the 1 to ~250 Hp (0.75 to ~185 kW} range has until recently prevented its adoption. High pressure die casting is the manufacturing method of choice for the aluminum rotor because of its inherently high productivity, low cost and ability to fill the slot of complex rotor bar shapes. Because of the high melting temperature of copper compared to aluminum, die life is drastically lower resulting in high tooling costs in attempts to die-cast the copper rotor. Recently these problems have been resolved by development of a high temperature nickel-base alloy die system, which when operated at elevated temperature, greatly extends die life [6]. This system is now in commercial use. Also, the French company, FAVI SA, has applied its considerable experience and know-how in die casting copper alloys to production of the copper rotor for a number of European motor manufacturers.

II. SEW-Eurodrive Industrial motors

SEW-Eurodrive has been active in an extended effort to design the motor to optimally use copper in the rotor. In April 2003, this company announced the availability of a range of EFF1 motors. Motors to 50 Hp (37 kW) are now available. The higher efficiency had been obtained in large part by employing electrical grade copper in the rotor although 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 and 5.5 kW motors at both 50 and 60 Hz.

Table I presents efficiency data for 1.1 kW and 5.5 kW SEW aluminum and copper rotor motors. Comparison of these motors is especially interesting because two different design concepts have been employed for the smaller 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 is of a higher grade.

TABLE I
FULL-LOAD EFFICIENCIES BY IEEE 112-B
FOR HIGH EFFICIENCY MOTOR SERIES DTE/DVE
AND STANDARD EFFICIENCY SERIES DT/DV

		50 Hz	60 Hz
Copper Rotor Motors			
DTE90S4	1.1 kW	82.8 %	84.1 %
DVE132S4	5.5 kW	88.1 %	89.7 %
Aluminium Motors			
DT90S4	1.1 kW	75.7 %	77.4 %
DV132S4	5.5 kW	84.8 %	86.6 %

In contrast, the high efficiency DVE132S4 (5.5 kW) has a completely new lamination and stator design. The design modifications relate to the starting behavior discussed below. The data in Table I show that the copper rotor leads to a significant increase in efficiency while maintaining the outer motor dimensions standard for aluminum – regardless of design.

To evaluate the efficiency contribution of the copper rotor, Fig. 1 shows the loss distribution for both motor ratings at 50 Hz. Fig. 2 contains the same data for 60 Hz operation. These figures clearly show that the main effects arise from reduced rotor losses. Especially for the 1.1 kW motor at 50 Hz operation, a decrease of more than 50% in rotor copper losses was observed. Because of the diagram scaling, the effect for 1.1 kW at 60 Hz 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.

A loss component which becomes more and more important with increasing power ratings are stray load losses (SLL). In Fig. 3 these losses for the motors of this study are compared.

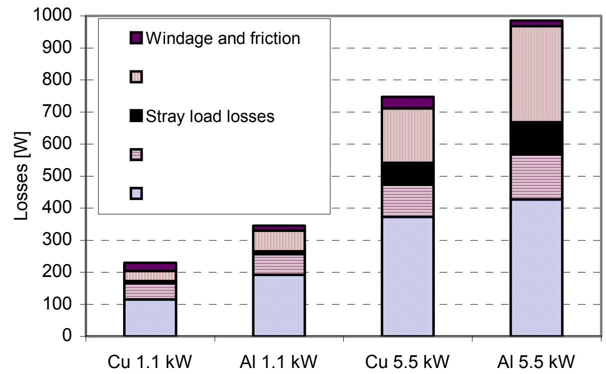

Fig. 1. Loss distribution at 50 Hz.

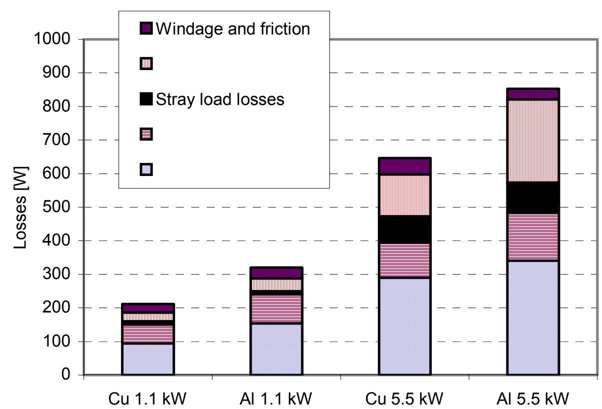

Fig. 2. Loss distribution at 60 Hz.

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Generally one observes that copper motors have lower SLL than their aluminum counterparts except for the 1.1-kW/60-Hz measurement where the SLL per unit input power is 0.57% for aluminum and 0.7% for copper. This might be due to a poor correlation in SLL estimation. In the aluminum case a correlation coefficient of 0.95 was calculated whereas all other measurements exhibit a coefficient of about 0.98 to 0.99.

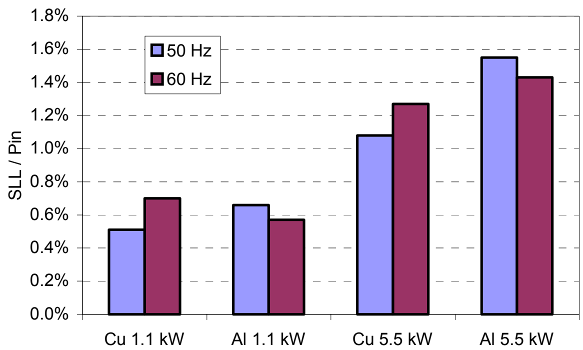

Fig. 3. Stray load losses per unit input power for 50 and 60 Hz

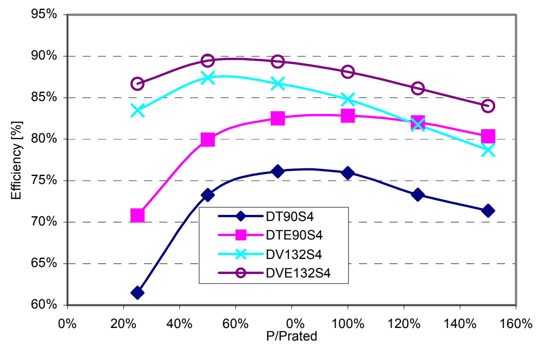

Fig. 4. Efficiency dependence on output power (50 Hz only).

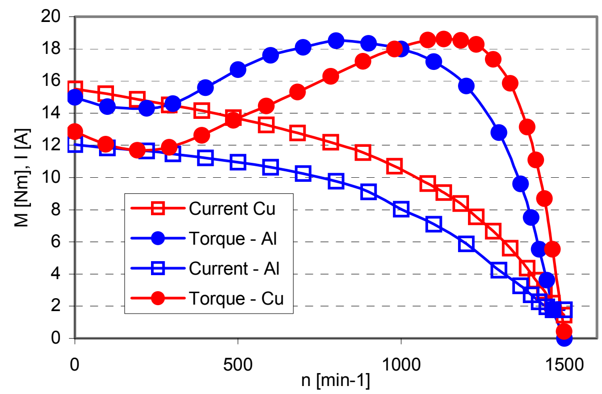

Fig. 5. Torque-speed and current-speed curves for1.1 kW motors. Standard efficiency Al motor (blue); Cu high effficiency motor (red).

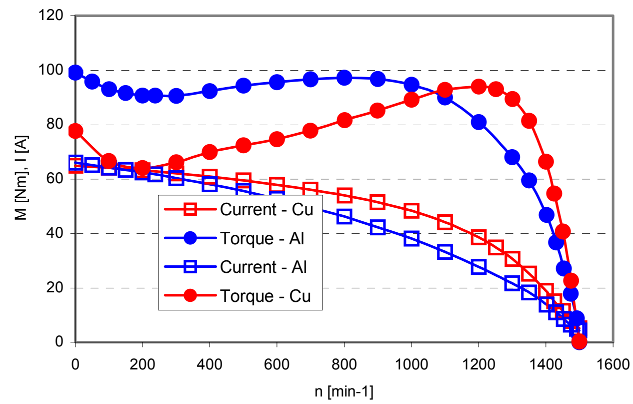

Fig. 6. Torque-speed curves for 5.5 kW motors. Standard efficiency Al motors (blue); Cu high efficiency motor (red).

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 Fig. 4 shows the dependence of efficiency on output power.

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. This 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 Fig. 5, 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. For that reason only minor design changes had been necessary for 1.1 kW motors.

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 Fig. 6 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.

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 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, in general, when the use of copper allowed reductions in rotor diameter, reductions in iron required for laminations, together with accompanying reductions in total manufacturing costs, the cost of the motor with an aluminum rotor at a given EPACT efficiency ranged from similar to 15% higher than the copper version. This cost saving for the copper rotor motor was in spite of the die-casting component of the copper rotor being typically three times more costly than the aluminum rotor.

III. A 10-HP INDUSTRIAL MOTOR

Another prominent motor manufacturer has recently compared the performance of a standard current production aluminum rotor motor with that of copper directly substituted for the aluminum and to a copper rotor where the lamination slot design had been redesigned to improve the locked rotor torque. The rotor lamination diameter was 5.722 in. and the stack length was 5.25 in. Both rotor designs contained 45 slots and had a starter bar connected to the slot by a thin web. The test data is summarized in Table II. End ring porosity due to die design issues in die casting the copper rotors was thought to potentially have an influence on motor test results, so the copper rotors were seperated into groups of higher porosity and those with less porosity. In the rotors cast in laminations with the aluminum slot design, more or less end ring porosity seems to have only subtle effect on the results. More importantly, substitution of copper for aluminum in the rotor increased the efficiency by 1.2 percentage points. If anything, the locked rotor torque increased slightly in the copper rotors and the locked rotor current increased by almost 25%. Maintenance of the starting torque in the copper version is apparently due to the fact that the aluminum slot design was equipped with a starter bar at the outer portion of the slot. Rotor assemblies C-7 through C-10 of Table II are rotors with a subtly modified slot design for copper. This slot design resulted in a considerable increase in locked rotor torque with little change in locked rotor current. The torque is now higher than that of the current production aluminum motor, but this was achieved at the expense of overall efficiency which has decreased by 1.8 percentage points compared to the die-cast copper rotor with the aluminum slot design and 0.7 percentage points below the production aluminum motor. The design objective of the manufacturer is not known. We observe that the copper slot design is very similar to the aluminum slot; i.e. both have an outer starting bar and a tapered running bar. The starter bar in the copper design is circular in cross section where that of the aluminum bar is five-sided, with the area of the copper bar being very slightly less. The tapered copper running bar is about 35% longer than the aluminum running bar extending deeper into the rotor, but the cross sectional areas of these two running bars and the leakage slot appear to be very similar.

TABLE II
SUMMARY OF TEST DATA FOR A 10 HP MOTOR
COMPARISON BETWEEN DIE-CAST ALUMINUM AND COPPER ROTORS

	Current Production Aluminum Rotors			Copper Rotors with Porosity-Al Slot			Copper Rotors with Less Porosity							
							Aluminum Slot				Copper Slot			
Rotor Assembly	G-1	G-2	G-3	G-4	G-5	G-6	C-2	C-3	C-5	C-6	C-7	C-8	C-9	C-10
Efficiency, %	90.5	90.3	90.8	91.9	91.8	91.7	91.7	91.7	91.8	91.2	89.8	89.9	90.1	89.5
Power Factor	.848	. 845	. 845	.845	.845	.846	.853	.858	.855	.856	.870	.866	.866	.861
RPM	1749	1751	1750	1773	1774	1774	1775	1776	1776	1776	1773	1774	1774	1773
LR Torque, ft-lbs	56.9	60.2	59.0	60.7	59.0	60.2	62.1	62.2	63.9	63.2	72.6	71.3	70.1	71.8
LR Current, amps	59.4	59.5	58.5	74.5	71.8	72.2	74.0	74.3	74.0	73.1	73.4	71.7	72.5	70.5

Voltage was 575 volts for all tests. Each rotor was tested in the same stator, frame and bracket assembly.
All tests at full load. Temperature normalized to 70°C.

IV. MOTOR TESTS IN INDIA

A project to test the suitability of the copper rotor technology upgrade for motors used for water pumping in agriculture in India was carried out by a cluster of motor and pump manufacturers at Coimbatore, Tamil Nadu. Copper rotors were cast by a small Indian die casting firm for all the tests. Rotor laminations designed for aluminum were used in this direct substitution evaluation. Motors were built and tested by six motor manufacturers. Field tests of motors fitted to pumps pumping water for agricultural use and one test of a motor driving a doffing machine in a textile plant were then conducted.

Results for two of the two-pole motors are shown in Tables III and IV and two 4-pole motors in Tables V and VI. All of these motors are 415 V, 50 Hz, 3 phase. As expected with a higher conductivity rotor material, the speed is increased slightly, the slip is reduced and the efficiency is increased. Starting (locked rotor) torque is also reduced somewhat when copper is substituted for aluminum in laminations with slots designed for aluminum as shown in Table VII. Copper rotors generally result in reduced motor operating temperatures compared to the aluminum counterpart. This is true in these examples except in the 2-Hp (1.5 kW) motor where the copper .rotor was cast with no cooling fins and the aluminum counterpart had fins. Even without fins, the motor with the copper rotor ran only about 3 °C warmer than the cooled aluminum rotor motor. The temperature rise data in Table VII were obtained by the winding resistance method.

TABLE III
TEST RESULTS FOR 2-HP (1.5 KW), 415-V, 2-POLE, 3- PHASE, 50-HZ MOTOR, COPPER ROTOR COMPARED TO ALUMİNUM

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	1824	2949	82.54
Aluminum	100	1856	2926	81.14
Copper	75	1440	2955	79.19
Aluminum	75	1456	2940	77.80

TABLE IV
TEST RESULTS FOR 5-HP (3.7 KW), 415-V, 2-POLE, 3- PHASE, 50-HZ MOTOR, COPPER ROTOR COMPARED TO ALUMİNUM

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	4256	2947	87.09
Aluminum	100	4496	2925	83.99
Copper	75	3232	2960	85.99
Aluminum	75	3408	2935	82.19

TABLE V
TEST RESULTS FOR 3-HP (2.2 KW), 415-V, 4-POLE, 3- PHASE, 50-HZ-MOTOR, COPPER ROTOR COMPARED TO ALUMİNUM

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	2600	1451	85.88
Aluminum	100	2660	1411	83.55
Copper	75	1960	1465	84.15
Aluminum	75	2040	1433	82.82

TABLE VI
TEST RESULTS FOR 5-HP (3.7 KW), 415-V, 4-POLE, 3- PHASE, 50-HZ MOTOR, COPPER ROTOR COMPARED TO ALUMİNUM

Rotor Material	Load (%)	Input Power, W	Speed, rpm	Eff. (%)
Copper	100	4344	1469	85.97
Aluminum	100	4544	1429	83.01
Copper	75	3280	1473	85.54
Aluminum	75	3400	1443	82.56

Field testing of three of the motors described above are summarized in Table VIII. The two-pole 2-Hp (1.5 kW) and 5 Hp (3.7 kW) motors of Tables III and IV were applied to pumping water for agricultural use. Voltages at many locations in India vary substantially over time. Table VIII shows that the field voltages were both higher and lower than the nominal 415 V. The tests comparing the pumping performance of motors with copper and aluminum rotors were decisive in terms of pumping time to fill the tanks and energy consumed in pumping a liter of water. The 2-Hp (1.5 kW) motor pump combination was tested filling a 2000 liter tank. The tank was brought near to the top in 823 sec. with the copper rotor motor, 170 sec. faster than with the aluminum rotor motor, a result of the higher rotational speed of the copper motor. But importantly, less total energy was consumed even at the higher pumping rate by the copper motor and the volume of water pumped per kWhr was 8.9% higher. The larger motor was tested filling a 5000 liter tank. Filling time was reduced by 82 sec. with the copper motor; i.e. 772 sec. vs. 854 sec. The volume pumped per unit of energy was increased by 10.1% by using copper in the rotor.

It should be noted that the increased speed of a low slip copper rotor motor can be a problem in pump and fan applications when higher flow rates are not desired. One might assume that energy would be wasted with the aluminum to copper rotor substitution because the power increases with the cube of the rotational speed. The increased flow rate efficiency actually observed apparently means that the increased electrical efficiency of the copper rotor was sufficient to result in an overall increase in pumping efficiency at the higher rotational speed. To the Indian farmer, the higher flow rate is actually a benefit. If this was not the case, adjustment of the gear or drive belt ratio could be done to keep the flow rate constant.

Table VII
LOCKED ROTOR TORQUE AND TEMPERATURE RISE MEASUREMENTS FOR 2- AND 4-POLE MOTORS, COPPER ROTOR COMPARED TO ALUMINUM

Hp	Poles	Rotor Mat'l	Locked Rotor Torque (% of rated torque)	Temp. Rise (°C)
2	2	Cu	406.2	39.6 [1,2]
		Al	442.2	36.8 [1,2]
5	2	Cu	174.0	66.7 [2]
		Al	260.9	80.1 [2]
3	4	Cu	242.4	57.7
		Al	268.4	68.8
5	4	Cu	168.4	61.8
		Al	205.2	68.9

[1] No cooling fins on this die-cast copper rotor.
[2] Measured at reduced voltage of 353 V.

TABLE VIII
FIELD TEST RESULTS FOR MOTORS OF TABLES III AND IV FITTED TO PUMPS FOR AGRICULTURAL APPLICATION

Motor/ Rotor Mat'l	Input Power, kW	V	Discharge Rate, l/sec	Energy kWh	l per kWh
2 Hp					
Cu	2.413	462	2.43	0.551	3,630
Al	2.171	446	2.01	0.599	3,333
5 Hp					
Cu	3.86	389	12.93	0.824	12,114
Al	3.77	377	11.71	0.894	11,003

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