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# Improving the High Speed Efficiency of xEV Induction Motors

## - Reducing Losses in Traction Motors with Die Cast Copper Rotors -

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**ABSTRACT**: Practical work on die cast motor rotors is presented that increases the high speed efficiency of induction motors used in electric vehicle traction. Processing and design features are reported that produce die cast copper rotors having improved motor efficiencies in-line with motors employing fabricated copper rotors. Two possible mechanisms are identified that explain the previously low efficiencies shown by die cast rotors at high rotational speeds. This work moves induction motors closer to being an effective low-cost replacement for today’s high-cost permanent magnet motors.

**KEY WORDS**: EV and HV systems, motor, non-ferrous material, material for motor, heat treatment, surface treatment / copper, die casting, induction motor, high speed efficiency [A3]

### 1. Introduction

As the popularity of hybrid and electrical vehicles (together “xEVs”) continues to grow, traction electric motors are becoming common in automotive applications. There are a number of different terminologies associated with these types of vehicles, including hybrid electric vehicles (HEV, such as the Toyota Prius), battery electric vehicle (BEV, such as the Tesla Model S), plug in hybrid electric vehicles (PHEV, such as the Toyota Prius Plug-In Hybrid) and extended range electric vehicles (EREV, such as the Chevrolet Volt), but all utilize an electric motor to provide at least some of the traction supplied to the vehicle’s drive wheels. Historically two different types of motors have been used in xEV applications, induction and DC brushless permanent magnet motors. For an induction motor, rotation is generated via magnetic fields from the stator inducing current in the rotor. The most common form of induction motors is a rotor similar to the one shown in Fig. 1, which comprises a series of longitudinal conductor bars (usually made of aluminum or copper) inserted into slots located towards the periphery of a stack of steel laminations. The conductor bars are connected at both ends by shorting end rings, producing what is known as a squirrel cage structure. In contrast, DC brushless motors typically employ permanent magnets in their rotors. Both motors use stationary coils in the motor housings to create the rotating magnetic fields that cause the rotor to spin.

The high energy permanent magnets used in DC brushless motors are typically made from neodymium and other rare earth materials, and while the prices of these materials were relatively low and stable until 2010, since then they have been subject to enormous price volatility, making it more difficult for xEV manufacturers to control and manage costs. In addition, induction motors typically have a significantly lower acquisition cost for xEV applications, compared with DC brushless motors. The price volatility in the rare earth markets has made induction motors more attractive for xEV manufacturers.

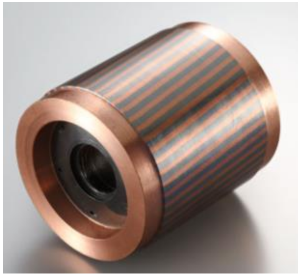

Fig. 1 Copper die cast rotor.

### 2. Reduced Efficiency of Induction Motors

As induction motors are typically less efficient than equivalent permanent magnet motors, efforts are continuously underway to improve their efficiency. One approach has been to develop more economic processes for making the squirrel cage from a highly conductive material such as copper. The squirrel cages for induction motors are typically produced from either aluminum or copper, and rotors can be manufactured by either die casting or a fabrication approach, where the squirrel cage is brazed together from a large number of machined pieces. The lowest cost approach for producing rotors is by die casting aluminum in the squirrel cage, but as the electrical conductivity of pure copper is more than 60% greater than that of aluminum, rotors constructed from copper generally produce motors of higher overall efficiency. However, the high melting point of copper (1083°C for copper versus 660ºC for aluminum) makes copper rotors more difficult and more costly to die cast. Historically, copper rotors (especially large rotors) have generally been produced using the fabrication approach, despite the high costs associated with assembly and brazing.

Over the past ten years, it has been recognized that, when the rotor is operating at the high rotational speeds associated with xEVs (up to 15,000 rpm), the efficiency of inverter-driven motors incorporating die cast copper rotors is slightly lower than motors using fabricated copper rotors (Fig. 2). This phenomenon is not apparent when the rotor is rotating at the lower speeds used in industrial motors (1,800-3,000 rpm), or with motors that are not inverter driven.

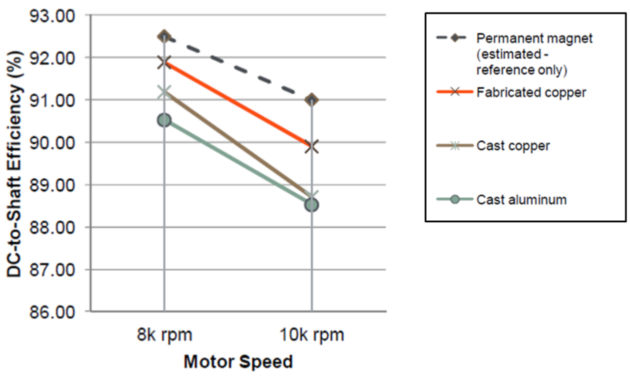


Fig. 2 Efficiencies of motor types at high rotational speeds.

This difference is surprising, as it might be expected that the efficiency associated with fabricated copper rotors would be lower, as the cages of fabricated rotors generally have higher electrical resistance due to the brazing material used in their manufacture. This is emphasized by the data in Table 1, which shows the theoretical resistance for 75 mm long aluminum and copper squirrel cage rotors. When comparing measured and calculated values, the aluminum and copper die cast rotors are close to theoretical, while the measured values for the fabricated rotors are significantly higher, again likely due to the brazing materials used in fabricating their cages. Accordingly the main purpose of this project was to identify the cause of the lower high-speed efficiencies of the copper die cast rotors, and identify processing conditions that produce copper die cast rotors having equal or even higher efficiencies than their fabricated counterparts.

Table 1 Effective internal cage resistance of three motor types.

| Item | Resistance (μΩ) | |
|---|---|---|
| | Calculated | Measured |
| 75 mm long fabricated copper rotor | 1.86 | 3.00 |
| 75 mm long cast copper rotor | 2.16 | 2.00 |
| 75 mm long cast aluminum rotor | 3.52 | 3.33 |

## 3. Methodology

All the test work used the 76mm long rotor design of an AC Propulsion AC-75 motor. The AC-75 is an air cooled three-phase induction motor designed specifically for automotive applications (Fig. 3). Specifications for the motor are listed in Table 2.

Fig. 3 AC-75 motor used in this study.

Table 2 Specifications for the AC-75 motor

| Item | Magnitude |
|---|---|
| Peak shaft torque | >115 Nm |
| Shaft power – peak | >75 kW |
| Shaft power – continuous | >25 kW |
| Rotor length | 76mm |
| Rotor diameter | 126mm |
| Number of conductor bars in rotor | 68 |
| Maximum speed | 13,000 rpm |
| Dry weight | 34 kg |

The production version of this motor uses a fabricated copper rotor. For the die casting trials described here, the design of the rotor was essentially unchanged, except that the length of the end rings was reduced from the 25mm used with the fabricated rotor to 15mm for the die cast rotor. As the electrical resistance of a cast copper end ring is lower than that of a fabricated end ring (due to the high number of brazed joints in the multi-part brazed end ring of the production AC-75), this length difference was analyzed as not negatively impacting efficiency.

The copper rotors were all die cast using the project's casting partner's standard production equipment.

The casting quality of the rotors was excellent, with minimum evidence of porosity as confirmed by sections taken at multiple points along the rotor and through the end rings.

This study systematically varied a number of process parameters, to determine the impact upon electrical efficiency of each parameter. The variable parameters used to produce the rotors are summarized in Table 3.

Table 3 Testing matrix. Rotors 19 thru 23 used the "standard" casting conditions, and for rotors 24 thru 37 one variable was adjusted for each casting. Rotors 19 thru 21 were destructively tested to confirm casting quality.

| Rotor No. | Quench after Cast | Post Cast Heat Treatment | Coated Slots | Alloy |
|---|---|---|---|---|
| 19 | N | N | Y | Cu |
| 20 | N | N | Y | Cu |
| 21 | N | N | Y | Cu |
| 22 | N | N | Y | Cu |
| 23 | N | N | Y | Cu |
| 24 | Y | N | Y | Cu |
| 25 | Y | N | Y | Cu |
| 26 | N | Y | Y | Cu |
| 27 | N | Y | Y | Cu |
| 28 | N | N | N | Cu |
| 29 | N | N | N | Cu |
| 30 | N | N | Y | Cu |
| 31 | N | N | Y | Cu |
| 32 | N | N | Y | Cu |
| 33 | N | N | Y | Cu |
| 34 | N | N | Y | Al |
| 35 | N | N | Y | Al |
| 36 | Y | N | Y | Cu |
| 37 | Y | N | Y | Cu |

Each of the variables examined in the study is discussed in more detail below.

**(1) Materials** - The majority of the rotors were cast using copper alloy C102 (high purity oxygen-free copper). The chemical specification for this alloy is listed in Table 4.

Table 4 Chemical composition specification for copper alloy C102[(1)]

| Element | Composition (wt.%) | | |
|---|---|---|---|
| | Nominal | Minimum | Maximum |
| Copper (incl. silver) | -- | 99.95 | -- |
| Residual Deoxidants | -- | None | |

For comparative purposes, several rotors were also die cast from aluminum alloy 170.1, and the chemical specification for this alloy is listed in Table 5.

Table 5 Chemical composition specification for aluminum alloy 170.1 (in wt.%)[(2)]

| Al min | Si | Fe | Mn | Cr | Zn | Ti | Unspecified Other Elements | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Each | Total |
| 99.7 (a) | (b) | (b) | (c) | (c) | 0.05 | (c) | 0.03 (c) | 0.10 |

(a) The aluminum content is the difference between 100.00% and the sum of all other metallic elements present in amounts of 0.010% or more each, expressed to the second decimal before determining the sum
(b) Iron/Silcon ratio = 1.5 minimum
(c) Manganese + Chromium + Titanium + Vanadium = 0.025%max

**(2) Laminations** – The main 0.35mm thick laminations used in this study were non-directional silicon steel, annealed after stamping. Two thicker (0.79mm) laminations were laser-cut from cold rolled steel and were placed at each end of the lamination stack to prevent lamination distorsion during the high pressure filling with molten copper.

**(3) Coatings Used in the Bar Slots** - After experiencing early problems filling the rotor during die casting, all rotors were cast after applying a proprietary ceramic coating to the whole assembled stack. This coating was applied by dipping the assembled lamination stack into a container of the coating material. A photograph at a typical ceramic coating thickness on the inside of the slots is shown in Fig. 4. The coating was approximately 0.05mm thick. This coating is typically used to provide a thermal barrier between copper and steel to prevent premature solidification during casting.

Fig. 4 Photograph of a slot in a test lamination stack, after the application of the proprietary ceramic coating.

**(4) Stack Preheat** - The stack preheat temperature was standardized to 425±28ºC.

**(5) Quench after Ejection from Die** - Once the cast rotors were ejected from the casting die, two different cooling regimes were examined: air cooling and a rapid water quench. In each case, the rotors were at a temperature of 350-370ºC when ejected from the die. The air cooled samples were simply allowed to naturally cool to room temperature. For the water quenched samples, 45 to 60 seconds elapsed from opening the die to plunging the castings into a tank of water. The tank contained 170-190 liters of water at an approximate temperature of 20ºC. No quenching additives were present in the water.

**(6) Post Cast Heat Treatment & Quench** - The impact of a post casting heat treatment upon rotor efficiency was also evaluated. Select rotors that had been air cooled to room temperature following ejection from the die were subsequently placed into a furnace pre-heated at 427°C for a period of 90 to 120 minutes. After removal from the furnace, the rotors were water quenched as described above.

Performance testing of the die cast rotors was carried out using a dynamometer (Fig. 5). Efficiency was calculated by comparing input power to the mechanical power developed, and measurement accuracy was 0.1% of full scale. All efficiencies measured were DC-to-shaft efficiencies and included the efficiency of the inverter, which previous experience showed to be constant. The same stator was used for all efficiency measurements, and each measurement presented in this paper is the average of five separate measurements.

Efficiency measurements were performed at two power levels (10 kW and 50 kW), two rotational speeds (8,000 rpm and 10,000 rpm), and at two rotor temperatures (50°C and 100°C). These parameters were chosen because it was known in the industry that they would demonstrate the difference between fabricated and cast rotors. Rotor temperature measurements were performed with an infrared pyrometer using the following procedure: rotor temperatures were monitored as they increased during operation, and efficiency measurements were performed once the rotors achieved a temperature of either 50°C or 100°C. Both end rings were painted black to ensure stable temperature readings.

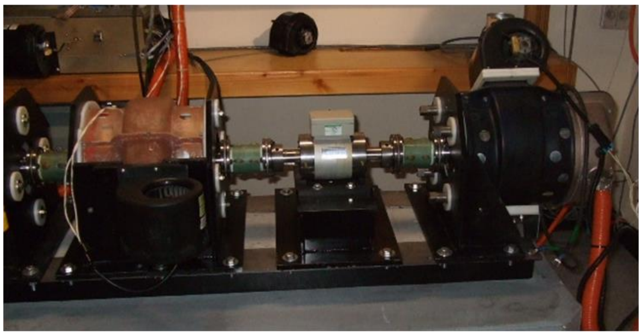

Fig. 5 Dynamometer used for efficiency testing.

## 4. Results

### 4.1 Electrical Tests and Quality of Cast Conductor Bars

Additional testing was performed to evaluate the quality of the conductor bars for each of the die cast rotors. The experimental set-up is shown in Fig. 6. A 50 amp DC current was applied between opposite sides of the two end rings, and a pair of probes used to measure the voltage drop across each conductor bar. If a conductor bar had poor cast quality, or had a total break (due to non-filling during casting), this would be revealed by a higher-than-calculated voltage drop.

This is a rapid, non-destructive test procedure used on manufacturing lines to confirm the quality of rotor cage integrity. In all the rotors tested in this study, the results of these electrical measurements were consistent, with acceptable quality of rotor integrity.

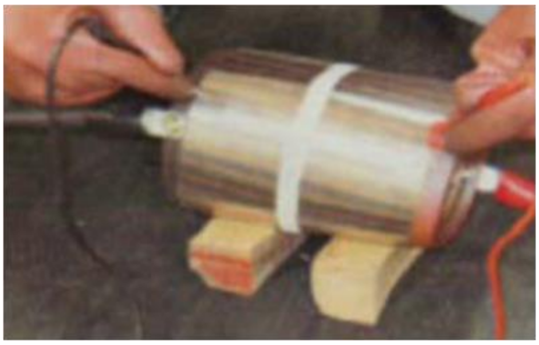

Fig. 6 Experimental set-up used to evaluate the quality of the conductor bars in the die cast rotors.

### 4.2 Chemical Analysis of Die Cast Rotors

The chemical composition of the copper used to produce the rotors was analyzed, to determine if impurities dissolved in the copper could be the cause of the observed efficiency reduction. Both the copper used to produce the rotors, as well as the copper from one of the cast rotors were analyzed. All elements (except oxygen) were analyzed using inductively coupled plasma mass spectrometry, while oxygen concentrations were determined using a Leco oxygen analyzer.

The measured chemistries are listed in Table 4. Elements chosen for analysis are those known to significantly reduce electrical conductivity. The only element showing any significant increase after casting was oxygen. Oxygen does not dissolve to any significant extent in a copper solid solution, but instead forms second phase particles with copper, so has an insignificant effect on electrical conductivity.

The conclusion is that the copper is not being contaminated by any impurities that significantly reduce its conductivity.

Table 4 Chemical impurity levels in copper used in the study.

| Element | Composition at Different Locations (wt.%) | | | |
|---|---|---|---|---|
| | Raw Material Pre-Casting | Gate End Ring | Surface of Conductor Bar | Opposite Gate End Ring |
| **Iron** | <0.001 | <0.001 | 0.003 | <0.001 |
| **Oxygen** | <0.001 | 0.12 | -- | 0.12 |
| **Phosphorous** | <0.005 | <0.005 | <0.005 | <0.005 |
| **Manganese** | <0.001 | <0.001 | <0.001 | <0.001 |
| **Silicon** | 0.008 | <0.005 | 0.015 | <0.005 |
| **Nickel** | 0.001 | 0.001 | 0.001 | 0.001 |
| **Chromium** | <0.001 | <0.001 | <0.001 | <0.001 |

### 4.3 Results from Dynamometer Testing

Die cast rotors 22 through 37 were all dynamometer tested using the equipment shown in Fig. 5. The casting parameters used to produce these rotors are summarized in Table 3. To provide baseline data, two fabricated copper rotors were also tested, one before and one after the cast rotors (to confirm absence of drift in the dynamometer test equipment).

The average loss in efficiency for each condition examined in this study is reproduced in Fig. 7. This data show that the four rotors that were water quenched immediately after ejection from the casting die have the lowest loss in efficiency: only 0.2% lower on average than the fabricated copper rotor. The "standard" casting conditions (including air cooling), and those rotors given a post casting heat treatment have slightly higher loss in efficiency: 0.50% and 0.57% higher than the fabricated copper, respectively.

The rotors cast without the proprietary ceramic coating had even higher loss of efficiency of 0.85%.

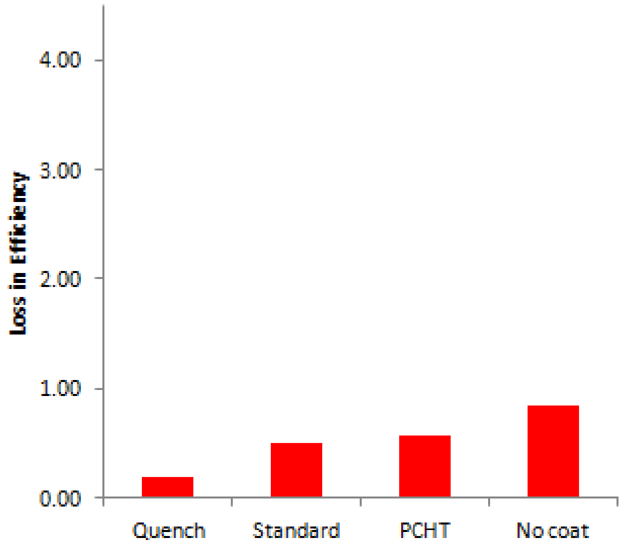


Fig. 7 Average efficiency loss for each condition examined.

The data shown in Fig. 7 indicate that quenching immediately after casting had the largest impact upon improving efficiency, while casting without the proprietary ceramic coating on the lamination stack degraded efficiency the most. These two observations suggest that minimizing physical and electrical contact between the die cast copper conductor bars and the lamination stack had the largest impact on efficiency improvements. It is likely that quenching immediately following casting breaks the cast conductor bars away from the lamination stack, due to the difference in coefficient of thermal expansion between the copper and the steel. The presence of the ceramic coating is believed to lower the copper-to-steel adhesion and promote breakaway. Performing an elevated temperature heat treatment after cooling the rotor to room temperature did not have a similar effect.

Fig. 8 summarizes these conclusions: it is a modified version of Fig. 2, and now includes the data for the efficiency of copper die cast rotors incorporating water quenching immediately after casting. This shows that the efficiency of motors utilizing die cast copper rotors can be made essentially the same as those using fabricated rotors by implementing a ceramic coating of the laminations and a water quench immediately after casting.

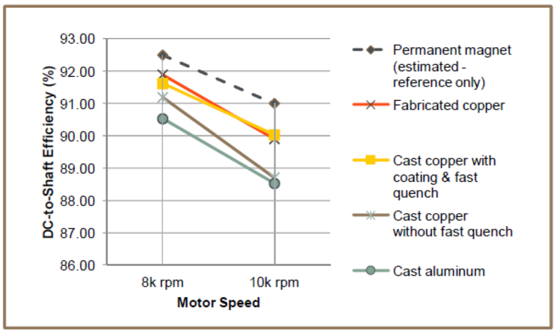


Fig. 8 Efficiencies of different motors at high rotational speeds, incorporating the data for the rotors water quenched immediately after die casting.

**4.4 End Ring to Lamination Resistance Measurements**

To further evaluate the impact of casting parameters on the level of physical and electrical contact between the cast copper and the lamination stack, additional measurements were made of the electrical resistance between the end ring and the lamination stack for rotors cast under different conditions. A 100A current was applied between the front end ring and the shaft rear end (which was in good electrical contact with the uninsulated lamination stack edges). To determine the electrical resistance, the voltage drop was measured between the front end ring and the rear shaft end using a digital volt meter. The results, which are summarized in Table 5, show very little difference between any of the copper rotors cast in this study, while the resistance measurements were about three orders of magnitude higher for the fabricated rotor.

It is surprising that the use of the ceramic coating together with quenching immediately after casting does not raise the electrical resistance between the die cast copper conductor bars and the lamination stack to the level of the fabricated rotor.

Table 5 Electrical resistance measurements between the front end ring and the lamination surface for rotors produced under different conditions.

| Rotor Number | Rotor Material | Condition | Resistance (μΩ) |
|---|---|---|---|
| 22 | Cu | Normal | 1.2 |
| 23 | Cu | Normal | 1.2 – 4.6 |
| 24 | Cu | Quench | 0.15 – 3.0 |
| 25 | Cu | Quench | 0.65 – 6.8 |
| 29 | Cu | No coat | 1.0 |
| 31 | Cu | Skew 3 | 1.3 |
| 34 | Al | -- | 13 |
| 35 | Al | -- | 5 - 7 |
| Fabricated | Cu | -- | 1,450 |

**4.5 Evaluation of Coatings on the Lamination Stack**

The proprietary ceramic coating applied to the bar slots of the lamination stack prior to casting has three intended functions – (1) to minimize heat loss from the molten copper to the cooler lamination stack (thereby maximizing castability), (2) to provide some level of electrical insulation between the copper conductor bars and the lamination steel, and (3) to provide a weakness zone from which the bar can pull away from the steel during the forces generated from the differential contraction during a quench.

To examine how well this coating was standing up to the injection of molten copper, several rotors were sectioned to directly examine the interface between the cast copper and the lamination stack. One such sample is shown in Fig. 9, which indicates that some of the ceramic coating material did survive the copper die casting process, and was still present on the surfaces of both the copper conductor bar and the slot. A brown material, believed to be iron oxide, was also present on the surfaces of the conductor bar and the laminations.

Fig. 10 shows a short length of a cast copper conductor bar, and the ceramic coating material is still present over at least a portion of the cast surface. The sample also clearly shows witness marks from individual laminations within the rotor stack, confirming that the copper does indeed make intimate contact with each individual lamination edge during the die casting operation.

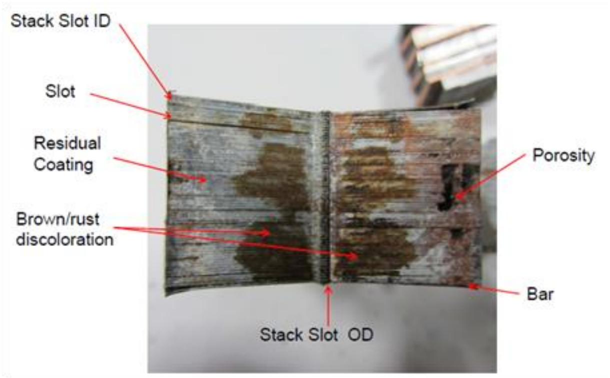


Fig. 9 Opened-up slot samples from a copper rotor, showing the surface of the cast copper conductor bar (right) and inside surface of the slot in the lamination stack (left).

Fig. 10 Short length of copper conductor bar taken from a die cast rotor.

### 4.6 Electrical Performance of Laminations after Casting

A separate series of bench-scale tests have been performed to determine whether heating of the lamination steel during the copper die casting operation negatively impacts its electrical performance. For the production of both fabricated copper rotors and aluminum die cast rotors, the laminations stacks are only heated to a relatively low temperature (a maximum of 800ºC and 700ºC, respectively), while the laminations are heated to a much higher temperature during copper die casting. This suggests the possibility that the magnetic properties of the lamination steel could be affected differently in copper die cast rotors as compared to both fabricated copper rotors and cast aluminum rotors.

To investigate this possible effect, two types of laminations were tested - as-received laminations, and laminators extracted from copper rotors after die casting. The electrical properties of the steel were tested at two locations for each lamination – adjacent to the slot outside diameter and adjacent to the slot inside diameter. Copper wire was wound around each of the laminations (as shown in Fig. 11), and the circuit in Fig. 12 used to test performance at each location.

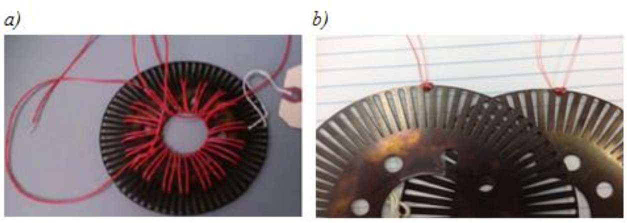


Fig. 11 Windings used to test electrical performance of the lamination steel.

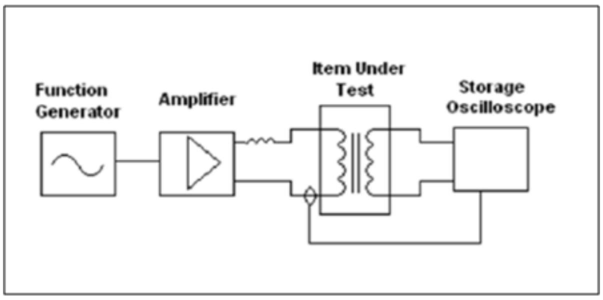


Fig. 12 Circuit used to test the electrical performance of the lamination steel.

Testing showed that the lamination steel located adjacent to both the inside diameter of the slot and the outside diameter of the slot showed only insignificant changes in electrical performance after die casting (Fig. 13). It is unlikely that a change in the steel's magnetic performance during die casting can explain the lower efficiency of the die cast rotors.

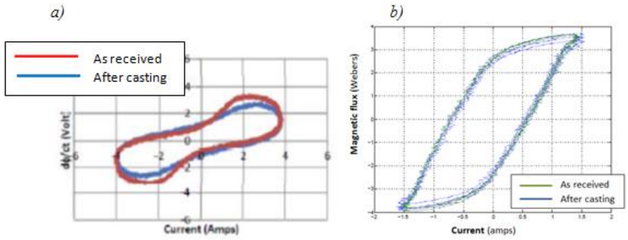


Fig. 13 Comparing electrical performance of the steel laminations before and after casting with copper.

a) Testing performed at the inside diameter of the slot using the configuration shown in Fig. 11a (at 1 kHz).
b) Testing performed at the outside diameter of the slot using the configuration shown in Fig. 11b (at 8 kHz).

### 4.7 Breakdown of Lamination Coatings

Lamination steel is typically precoated with so-called C5 organic or inorganic coatings to prevent losses from lamination-to-lamination shorting through contacting lamination faces. To evaluate possible effects from the high temperatures seen by these coatings during copper die casting two industry-standard C5 coatings were examined, type 5308 and type 5620. Both the 5308 and 5620 materials are an inorganic/organic hybrid coating with inorganic insulating pigments and are specified as resistant to continuous exposure to temperatures of above 270°C. Phosphoric acid in the liquid coating forms an iron phosphate layer on the steel lamination, which should survive the molten copper temperatures. Samples of both coatings were subjected to tests performed on small rectangular coated steel plates. Those samples were dipped into baths of either molten aluminum (at 705ºC) or molten copper (at 1300ºC). Fig. 14 shows the results from the testing, indicating that while both the aluminum and the copper adhered somewhat to the samples, the copper buildup was more extensive and thicker (about 0.25 mm per side).

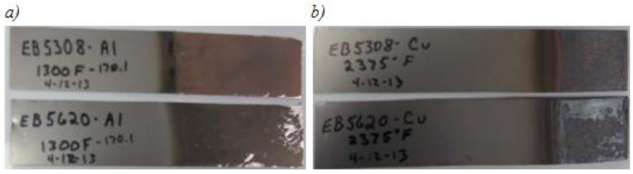


Fig. 14 Surface condition after immersion of samples 5308 and 5620 into molten metals.

a) Molten aluminum.
b) Molten copper.

To further quantify this testing, electrical resistance measurements were performed to determine the degree to which the coatings were still intact after immersion. Probes were used to perform the measurements at the following three locations (see Fig. 15):

- Probe location 1 – Coating removed by mechanical abrasion.
- Probe location 2 – Undisturbed, un-dipped coating.
- Probe location 3 – Sample area immersed into molten metal.

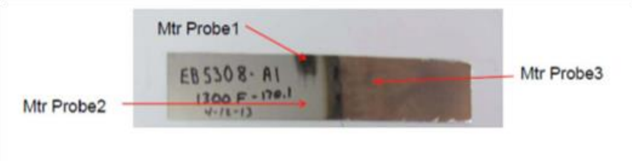


Fig. 15 Locations uses to test electrical resistivity.

The electrical resistance results are summarized in Table 6, which shows that the electrical resistance was lower for the samples dipped into molten copper. However, these resistance measurements are still high (22,000 Ω), and would most likely be adequate to insulate the laminations from each other. These results suggest, therefore, that both these coatings could be suitable for copper die cast rotors.

Table 6 Results of electrical resistivity measurements on coating samples 5308 and 5630 after dipping into molten aluminum or molten copper.

| Coating | Liquid Metal | Probe Locations | Resistance (ohms) |
|---|---|---|---|
| 5308 | Aluminum | 1 + 2 | ∞ |
| | | 1 + 3 | ∞ |
| 5620 | | 1 + 2 | ∞ |
| | | 1 + 3 | ∞ |
| 5308 | Copper | 1 + 2 | ∞ |
| | | 1 + 3 | 22,000 |
| 5620 | | 1 + 2 | ∞ |
| | | 1 + 3 | 22,000 |

## 5. Discussion

The data presented in Fig. 7 and Fig. 8 of this report indicate that conditions have been identified that improve the efficiency of motors using die cast rotors, bringing their efficiencies in-line with motors using fabricated rotors. The two parameters that had the largest impact on improving efficiency were water quenching of the rotor immediately upon ejection from the casting die, along with the use of a ceramic coating applied to the inside of the bar slots in the assembled lamination stack. Both of these parameters appeared to isolate the conductor bars from the lamination stack, physically thermally and, to some extent, electrically.

During this study, five explanations were generated and tested as being possible mechanisms responsible for the lower efficiencies of the die cast rotors. It is worthwhile discussing each of these mechanisms in relation to the results of this study. In the following sections, each of the five mechanisms is initially presented followed by a brief discussion of the results from this study in relation to the proposed mechanism.

**(1) Increased Bar-to-Lamination Shorting (possible)** - During solidification, the liquid copper that fills the bar slots in the assembled lamination stack is subjected to a very high pressure. The liquid copper in the slots is pushed against the laminations, and so makes better contact with the laminations than the copper rods inserted into the slots of fabricated rotors. Electrical shorting between the rotor bars and the laminations of die cast rotors could increase either circumferential parasitic currents from bar-to-bar or inter-laminar currents. The losses associated with this mechanism are likely to be higher when the rotor is spinning at high speeds (10,000 rpm versus 1,800 rpm), as centrifugal forces push the copper conductors bars against the lamination stack.

The impact upon efficiency of quenching after casting plus the use of the ceramic coating (shown in Fig. 7 and Fig. 8) suggest that electrical shorting between the rotor bars and laminations could indeed be the cause of the reduced efficiency. The mechanism of efficiency reduction associated with bar-to-lamination shorting is not fully understood. Further work is needed to identify coatings that will improve the level of insulation between the conductor bars and the laminations.

**(2) Low End Ring Resistance (possible)** - The end rings of fabricated rotors are made up from the brazing together of ring sectors to form a whole ring. In this construction the end rings have higher electrical resistance than die cast end rings due to the brazing material used in their fabrication. It is possible that this high resistance is reducing frequency-dependent losses that are apparent in the pure copper cage.

No attempt was made in this project to examine the impact of the electrical conductivity of the brazed rotors on motor efficiency. This remains a possible mechanism behind the lower die cast rotor efficiencies. Furthermore, if this is the actual mechanism, then the coating-and-quenching method could be able to increase the efficiency of die cast rotors above that of fabricated rotors if higher resistance end rings are introduced to die cast rotors.

**(3) Degredation of Lamination Magnetic Properties (discarded)** - The web in the laminations at the outer diameter of the slots is very thin and so will be heated to a very high temperature during casting and solidification of the liquid copper. It was postulated that this high temperature could degrade the electrical and magnetic performance of the steel, leading to higher losses.

However, data shown in Fig. 13 suggest that heating of the lamination steel during the copper die casting process has not significantly impacted the electrical properties of the steel. This proposed mechanism, therefore, has been discarded.

**(4) Lamination-to-Lamination Shorting (discarded)** - The laminations have a coating on their surfaces. The high temperatures associated with copper die casting could cause thermal breakdown of the coating, allowing lamination-to-lamination and lamination-to-end-ring shorting.

The data from Table 6 indicates that some breakdown of the C5 lamination coating has occurred during the copper die casting process, but the post-breakdown resistance of the lamination-to-lamination insulation is still high enough to be adequate. This explanation, therefore, has been discarded.

**(5) Copper Contamination (discarded)** - Minor contamination of the liquid copper by impurity elements can significantly reduce electrical conductivity, thereby reducing overall efficiency of the motors.

Testing of the chemical composition (Table 4) indicates that contamination of the liquid copper did not occur, and so this is not the reason for the lower efficiency associated with die cast copper rotors. This mechanism was also discarded..

## 5. Conclusions

This work identified procedures that can be used to produce die cast copper rotors that develop efficiencies at high rotational speeds similar to those of fabricated copper rotors. The two casting parameters identified as significantly improving efficiency are:

- Quenching of the rotor immediately upon ejection from the casting die
- Use of a ceramic coating applied to the inside of the bar slots in the lamination stack

The work identified two possible mechanisms that may be behind the poor high speed efficiencies previously shown by die cast copper rotors:

- Electrical shorting between the rotor bars and the laminations of the die cast rotors originating from the high level of bar-to-lamination conformity produced by the die casting process.
- High resistance of the fabricated end rings reducing frequency-dependent losses that are apparent in the pure copper cages.

As manufacturers of electric vehicle traction motors incorporate the learning from this project into their products, the low-cost induction motor architecture will move one step closer to being an effective replacement for today's high-cost permanent magnet traction motors.

## References

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