DIE CASTING COPPER MOTOR ROTORS: MOLD MATERIALS AND PROCESSING FOR COST-EFFECTIVE MANUFACTURING

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ABSTRACT

This project seeks to demonstrate mold materials for copper pressure die-casting that are cost-effective and practical for production use in die-casting copper motor rotors. The incorporation of die-cast copper for conductor bars and end rings of the induction motor in place of aluminum would result in attractive improvements in motor energy efficiency through reductions in motor losses ranging from 15% to 20%. Die-cast motor rotors are produced in aluminum today because rotor fabrication by pressure die-casting is an established practice. Lack of a durable and cost-effective mold material has been the technical barrier preventing manufacture of the die-cast copper rotor. This project tested H-13 steel die inserts that establish the baseline. Nickel-, tungsten-, and molybdenum-based high temperature alloys were extensively tested. Results indicate that substantially extended die life is possible using high temperature die materials, pre-heated and operated at elevated temperatures. Pre-heating and high operating temperatures were shown to be critical in extending the die life by decreasing the cyclic stresses associated with thermal expansion. Extended die life provides the opportunity for economically viable copper motor rotor die-casting.

INTRODUCTION

It is well known that incorporation of copper for the rotor conductor bars and end rings in the induction motor in place of aluminum would result in attractive improvements in motor energy efficiency due to copper's exceptional electrical conductivity.

Die-cast motor rotors are universally produced in aluminum today because fabrication by pressure die-casting is a well-established and economical method. Only small numbers of very large motors utilize copper in the rotors by mechanical fabrication. Such fabrication involves intensive hand labor and therefore is expensive. Die-casting, when it can be performed, is widely recognized as a low cost manufacturing process. For these reasons, die-casting has become the fabrication method of choice and aluminum the conductor of choice in almost all but the largest frame motors. Tool steel molds as used for the aluminum die-casting process have proved to be entirely inadequate when casting higher melting point metals including copper. Lack of a durable and cost-effective mold material has been the technical barrier preventing manufacture of the die-cast copper rotor.

An important study sponsored by the US Department of Energy found that motors above 1/6 Hp used about 60% of the electricity generated in the United States.[1] When extrapolated worldwide, the potential economic and environmental benefits of this project are substantial. Medium horsepower motors, 1-125 Hp (0.75 to approximately 100kW), use about 60% of the electricity supplied to all motors in the US. Because of the proliferation of electric motors in this horsepower range, the target of this project, the projected energy savings of the copper rotor motor is a significant national consideration. Efficiency increases (a function of motor size) from improved electrical conductivity are projected to result in total US energy savings in the year 2010 of 20.2 E+12 Btu/yr at only 10% market penetration and 143 E+12 Btu/yr at the expected market penetration of 50 to 70% (dependent on motor size). These numbers for the US are equivalent to the yearly output, respectively, of 0.5 to 3.5 600 MW generating plants operating at 75% of capacity.

This research project is funded jointly by the International Copper Association, Ltd. (ICA) through the US Copper Development Association Inc. (CDA), the U.S. Department of Energy (DoE) through their NICE[3] program, and the Air Conditioning and Refrigeration Institute (ARI). Additional sponsors include ThermoTrex, Formcast, and motor manufacturers. The objective of this research is to identify high temperature, thermal shock resistant materials, and then to design, fabricate and demonstrate molds and processing conditions designed to withstand the copper motor rotor die-casting environment for an economically acceptable life, i.e., thousands of casting cycles.

[1] Classification and Evaluation of Electric Motors and Pumps, DOE/CS-0147, February, 1980

Several candidate die materials were identified; tungsten and molybdenum based refractory metals, beryllium-nickel, nickel-based superalloys, and one or more compositions in the tungsten-based composite family produced by a high-speed chemical vapor deposition (CVD) technique by the Trex Enterprises. This project in its *first* phase fabricated and tested a mold design (simulating the gate and volume of molten copper for a rotor mold) with inserts of the several mold materials for testing on a Buhler, 800-ton horizontal-shot-controlled pressure die-casting machine located at Formcast, Inc., in Denver, Colorado. In the *second* phase of this project, the most promising mold materials from Phase I are being fabricated into motor rotor molds and will be run for an extended number of shots at this same facility. For these runs, motor company partners will supply iron lamination stacks for appropriate motors designed to use copper rotor conductors. The motor partners will test the performance of the die-cast copper rotors.

BACKGROUND

Motor manufacturers currently offer standard efficiency motor designs, and many offer one or more higher efficiency designs at price premiums. Operating energy efficiency improvements have been a strong emphasis since the late 1970's in the US, when many aluminum stator windings were replaced by copper. Newer designs have recently improved efficiencies further by increasing the amount of copper in windings, additional core and copper coil size, reduced windage losses, improved core steel, etc. However, the rotor remains die-cast aluminum because long-lived molds are not available.

Recent analysis by two U.S. motor manufacturers shows that the economics of motor operation and manufacture favor the use of copper in all classes of motors if the die life in the pressure die-casting process can be extended to the order of 20,000 shots.

Die-cast copper rotors can provide advantages to motor manufacture and/or performance in three ways:

- improvement in motor energy efficiency in operation
- reduction in overall manufacturing cost
- reduction in motor weight .

The motor manufacturer can accentuate one of the advantages at the expense of the other two. For example, in the case of a premium 10 Hp motor recently analyzed, the motor efficiency is 91.0%, as tested by IEEE Method 112-B. It should be noted that for a similar 10Hp (7.5kW) motor, the minimum efficiency levels, as tested by true input/output methods such as IEEE, or CAS, are 89.5% as required by the US Energy Policy Act (EPACT), and 91.7%, as currently recommended for minimum "premium" efficiency by the US Consortium for Energy Efficiency (CEE).

Three design scenarios using cast-copper-rotors (CCR) have been analyzed: (1) seeking maximum efficiency improvement; (2) seeking maximum manufacturing cost reduction; and (3) seeking motor weight reduction.

Motors losses result from primary (stator winding) I^2R (usually 34% to 39%), secondary (rotor) I^2R (usually 16% to 29%), iron (core), friction and windage, and stray load.[2] In addition to direct reduction in rotor loss with CCR's, designs achieve additional reductions from overall motor re-optimization of iron, strays, etc. CCR-based designs show overall loss reduction from 15% to 20%.

(1) If motor re-design efforts were devoted solely to improving efficiency, it is estimated that the new design with CCR could achieve 92.5% efficiency. This CCR example creates a "super" premium efficiency motor with an efficiency level (i.e., 92.5%) higher than currently available premium efficiency motors.

(2) If motor re-design efforts were devoted solely to reducing manufacturing costs for the current 91.0% efficient premium motor, it is estimated that the new design using CCR could be manufactured at a $36 reduction in overall manufacturing cost (15% of current $240 estimated manufacturing cost), maintaining exactly 91.0% efficiency.

(3) If motor re-design efforts were devoted solely to reducing motor weight, it is estimated that the new design could reduce weight by 5% to as much as 10%.

In addition, CCR could be utilized to reduce rotor I2R losses in an existing motor design, (replacing the existing die-cast aluminum rotor, not re-designing the motor to include more/better quality core, more stator windings, etc.—the existing methods to achieve higher efficiencies), in order to improve motor energy efficiency in operation.

CCR's can be used in specific motors to achieve a multiplicity of intermediate combinations of these design advantages. For example, where a smaller efficiency increase is required, the CCR could be used to achieve some reduction in manufacturing cost (stator winding, core, etc.) than would otherwise have been the case with traditional aluminum die-cast rotor technology.

The problem encountered in attempting to die-cast copper motor rotors is thermal shock and thermal fatigue of mold materials. Thermal cycling of the mold surface limits the mold life even in aluminum die-casting. However, cyclic thermal stresses are so severe in copper die casting that in at least one recent instance, a mold-gate-plate made of high strength steel (H-13, a die casting industry standard) being tested fractured in fewer than 10 casting shots. To be economically feasible, mold life must be measured in thousands of casting cycles.

INNOVATION

A problem with common mold materials is that they lose strength at high temperature thus requiring low mean operating (and pre-shot surface) temperatures. A low initial temperature results in a large ΔT at the surface of the die, and thus the stress in the die, on

(2) Steels for Laminations in Energy Efficient Motors, CMP/EPRI Report 9-11, June 91 Table 2-1

each shot. The high melting temperature, high heat of fusion, substantial latent heat and high thermal conductivity of copper combine to maximize the thermal shock.

As a starting point, the solution to the thermal shock problem lies in the use of high temperature materials having thermal and thermo elastic properties conducive to minimizing thermally induced strain. Studies conducted by the International Copper Research Association (INCRA) in the 1970's confirm these expectations.

A major innovation in our program is in the process handling of these mold materials; we are die-casting with these high-temperature, high-performance materials when they are pre-heated (to elevated temperatures) to reduce this thermal differential and, thus, reduce the thermal shock to the molds within each cycle. Extended mold life appears feasible with several of our materials tested with this reduced temperature differential. In addition, the higher the pre-heat temperature (e.g. the lower the thermal differential) with several of our tested mold materials, the greater the reduction in heat-checking tendencies (or the longer in-service life before any heat-checking).

Tungsten and molybdenum were identified in the INCRA studies as good candidate materials for copper die-casting; however, they have not found extensive use in industry largely because of high base metal and fabrication costs. These refractory materials hold promise for long life (we included TZM, Anviloy, and Trex's tungsten Chemical Vapor Composite (CVC) materials in our testing). However, they formed oxides at our testing temperatures and may be still more expensive than necessary for all components of the mold system. Two promising candidates for mold material are the nickel-based super alloys (we tested 617, 625, 718, and 754) and the beryllium-nickel alloys. None of these materials has the low expansion of tungsten or molybdenum, but they do retain exceptional strength at high temperatures, and the Inconel alloys especially demonstrate good oxidation resistance at our operating temperatures.

Some of these high-temperature, high performance materials have been available for many years. Our efforts indicate that the large thermal differential when die-casting copper requires that the mold be pre-heated (reducing the thermal differential), in order to achieve a longer, economically viable mold life. In contrast, traditional die-casting uses molds to solidify, and reduce the molten metal temperature rapidly.

RESULTS

An Inductotherm melting furnace was installed for *phase 1* at Formcast in Denver, Colorado, capable of continuously melting eight pounds of copper at 2-minute intervals for successive die shots for feeding to the 800-ton Buhler real-time, computer controlled, die-casting machine at this facility. A test mold was designed to simulate the action at one gate of a multi-gate mold. Die casting trials of candidate mold materials do not incorporate the iron lamination stack because of the high cost of lamination material involved in the thousands of shots of testing candidate mold materials.

Figure 1. Inductotherm melting furnace in operation.

H-13 Tool Steel

Efforts were directed at evaluating a number of different high-temperature mold materials. Since the dies operated at very high temperatures, only materials designed for high-temperature service are under consideration for use in these molds (e.g., nickel-based super alloys and refractory metals such as tungsten and molybdenum). However, to establish a baseline for the test mold, the first copper die-casting trial was conducted using the H-13 steel die inserts (Figure 2). As expected, the dies generally degraded with increasing usage. Quite surprisingly, although some heat checking of the H-13 steel mold inserts and shot sleeve was evident after 20 shots, an extended run with copper against H-13 was accomplished. This success is attributed to the dry mold release system, the fast cycle time, which minimizes heat input to the mold, and through the use of advanced computer controlled casting equipment. Over 800 castings were produced using one set of dies, exceeding expectations by an order of magnitude. (Figure 3)

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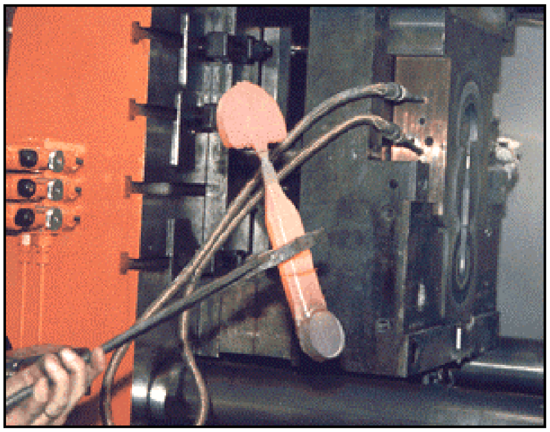

Figure 2. Copper die-casting.

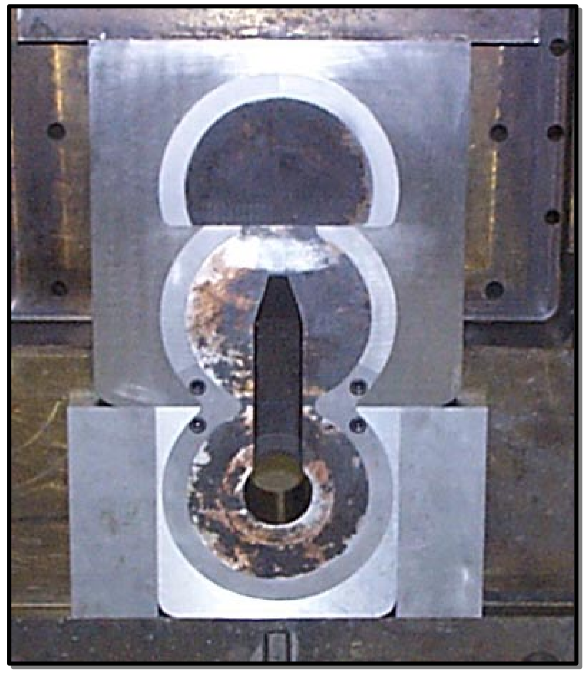

Figure 3. The H-133 steel test cavity tool set after the first several shots.

Several copper castings were metallurgically, chemically and physically analyzed. The gate and runner macrostructures showed an outer columnar chill zone and a mixture of equiaxed and columnar grains in the bulk. The microstructures also showed the presence of an interdendritic phase most likely a eutectic copper-oxygen phase. Surface cracks and tears were found in the gate sections, in general the number and depth decreased with shot number. Internal defects resembling oxide films, macroscopic pores and slag type inclusions were also found and again decreased in size and frequency with shot number. A small amount of porosity was also present within the castings, but the overall microstructures are sound (Figure 4). The electrical conductivity measurements taken from the castings averaged 98% IACS and varied between 95% to 101% IACS. Samples were chemically analyzed for oxygen and iron contamination. The iron content varied from 10 ppm to 350 ppm and the oxygen levels from 0.06% to 0.15%.

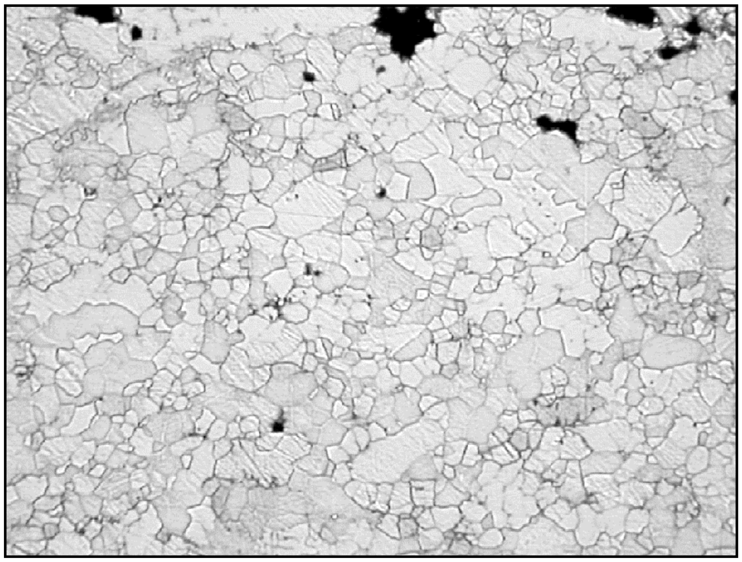

Figure 4. Photomicrograph of die-cast copper. Microporosity is a common defect associated with the die-casting process. 50X

Nickel-Based Superalloys

Die inserts were machined from Inconel alloys 617, 718 and 754. Over 250 die-castings were performed using these die sets, with the Inconel mold inserts pre-heated to over 300C. The Inconel 754 set began cracking very early (50 shots) into the run. This was somewhat surprising in that this particular alloy exhibits the highest strength at temperature of the three nickel-base alloys tested. But this alloy also has very low ductility at elevated temperature. The alloy with the lowest strength at temperature, Inconel alloy 718 began cracking after about 100 shots. The best performing alloy was the Inconel alloy 617, which exhibits the best combination of strength and ductility at elevated temperatures. Only minor craze cracking was evident on these die sets after 250 shots. These data provide an important clue toward solving this engineering problem, namely that a high fracture toughness at the service temperature may be important toward reducing the propensity to cracking and ultimately achieving extensive mold life.

Three copper castings were metallurgically, chemically and physically analyzed. Traces of iron, nickel and oxygen contamination were evident. Again, a small amount of microporosity was present within the castings, but the overall microstructures were sound. The electrical conductivity was better than that produced with the steel molds, nearly 100% IACS. To retain such high conductivity after melting in an open air environment and casting through a steel shot sleeve into nickel molds is very promising, as this will allow the copper scrap to be completely recyclable within the foundry.

A new set of Inconel 617 and 625 mold inserts was fabricated, and are presently being tested (targeting 650 C. preheat) for an extended run (over 1000 shots). The objective is to determine mold processing temperatures at which no mold degradation is evident after an extended run with these mold materials (the most promising of the Inconel mold materials tested to date).

CVD Tungsten

Tungsten inserts were fabricated by a high-speed chemical vapor deposition (CVD) technology developed by Trex Enterprises, San Diego, California. This technique offered the advantage of net-shape or near-net-shape fabrication on a graphite mandrel. An appropriate backing for the relatively thin tungsten or tungsten rhenium alloy shape remains to be developed. In the meantime the tungsten deposition was applied to a machined TZM molybdenum performs. Copper die-castings of the shape shown in Figure 2 were produced at Formcast. Tool life of the CVD tungsten molds has been disappointingly short at this point largely due to the columnar grain structure of the tungsten. Subsequent modifications to the mold set at Formcast to raise the tool temperature and efforts by Trex Enterprises to refine the grain structure are expected to considerably improve the life of tooling made by this technology.

TZM (Molybdenum Alloy) and Anviloy (Tungsten Alloy)

These alloys were considered in the early INCRA work on mold materials for pressure die-casting of copper, but their high ductile-brittle transition temperatures threaten survival of molds, especially in the first few shots. The solution is to pre-heat the molds by electrical resistance heaters.

TZM and Anviloy alloys were machined into die sets. They were heated to about 500 C before and during the die-casting trial. Over 500 shots were made with these die sets. There was some limited oxidation on both the TZM and Anviloy dies. However, no cracking due to heat checking was evident. The performance of these two die materials was unparalleled (Figure 5 - Left). Experience with these dies has shown that increasing the die operating temperature limits the thermal expansion and contraction, thereby decreasing the propensity to thermal fatigue cracking, more commonly known as "heat-checking." It is expected that further increasing the operating temperature of the dies will greatly extend their life by limiting the amount of cyclic strain associated with heating and cooling. It is predicted that operating the dies at elevated temperatures (just below the freezing point of copper) will limit the propensity for heat checking, thereby extending the life of dies to thousands of cycles.

Additional testing of these dies has recently been completed. Over 940 total die-castings have been produced. The TZM and Anviloy show minor cracking at the ejector pin locations, as shown in Figure 5 (Right); this cracking was due to inadequate allowance for thermal expansion in the steel ejector pins, and is able to be easily corrected. Otherwise, these molds showed long-life in die-casting service, without heat checking in the contours, gate areas, flat surfaces, etc., to a remarkable extent. With these results, further shots with these dies were not pursued, in order to install the new Inconel 617 and 625 insert set and begin that extended-life run, at higher pre-heat temperatures. Results to date show for these die materials that the higher pre-heat temperatures produce the substantially improved mold life, as anticipated.

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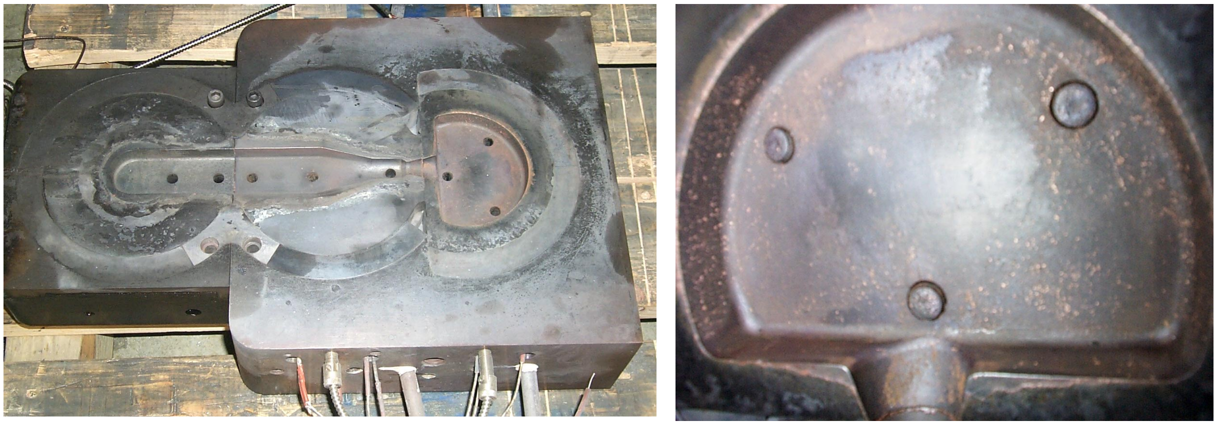

Figure 5. Left: Moving half of die set containing the TZM and Anviloy materials. Right: Close-up of Anviloy die after 500 shots. No thermal fatigue cracking (heat checking) was evident.

Inconel Alloy Dies

The new Inconel insert set shows little degradation in the mold set with over 600 shots already run, using the higher pre-heat temperature (Figure 6). A run of 1000 shots is planned for the Inconel alloy die set. After 300 shots, there is no evidence of cracking. Oxidation in and around the dies appears self-limiting. It is becoming increasing clear that operating the dies at elevated temperature is absolutely essential toward improving the die life. The dies are being operated at elevated temperature (600 to 650 C) to reduce the thermal expansion and contraction associated with casting and subsequent cooling. Limiting the cyclic expansion and contraction is helping decrease the thermal fatigue.

Figure 6. Fixed die half with Inconel alloy die inserts after 300 shots. The dies have oxidized a little but have not cracked after 380 shots.

Rotor Die Set

A die set was purchased from Buhler in Switzerland. The die set is presently being machined to fit the Buhler die-casting machine at Formcast in Denver. (Figure 7) Drawings were made for machining die inserts for producing rotors.

Inductotherm constructed and delivered an induction-heating furnace capable of melting 20 pounds of copper in less than 8 minutes. This furnace upgrade is necessary to die-cast the copper rotors. (Figure 8)

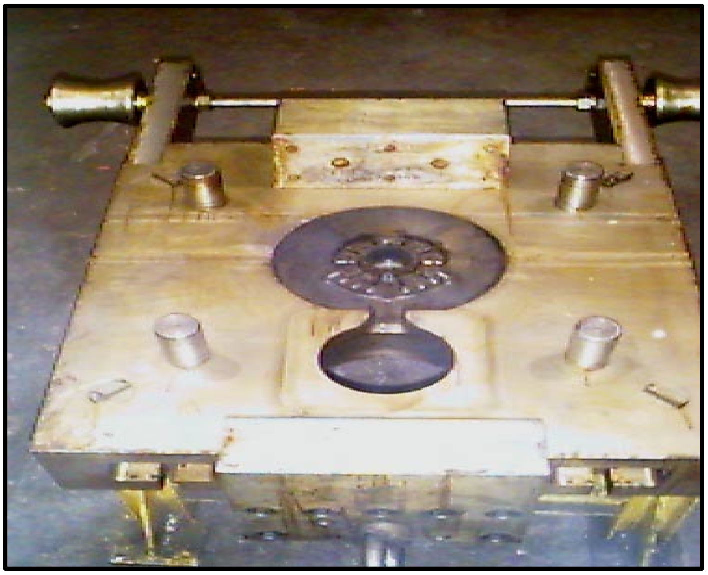

Figure 7. One section of the die set purchased from Buhler for die casting copper rotors.

Figure 8. Large Inductotherm melting furnace capable of rapidly melting over 20 pounds of copper.

SUMMARY

Copper die cast motor rotors would result in attractive improvements in motor energy efficiency. Advances have been made toward the development of durable and cost effective mold materials, presently the last major hurdle preventing die-casting of the copper rotors. An extended run of copper against TZM and the tungsten alloy Anviloy was accomplished without major heat checking.

A major innovation in our program is its design to reduce the thermal differential through pre-heating to high temperature the mold material (raising the operating mold insert temperature), in order to reduce thermal shock when contacted by the copper. With this technique, several high temperature, high performance materials may have long-life in copper motor rotor die-casting.

A new, long run with Inconel 617 and 625 is underway, and is anticipated to exceed 1000 shots and demonstrate no die degradation, using even higher die pre-heat temperatures (targeting 650 C.) to improve upon the earlier Inconel test results (conducted at die pre-heat over 300 C.). Increasing the operating temperature of the dies has shown to date that it extends their life by limiting the amount of cyclic strain associated with heating and cooling. The use of high pre-heat temperatures with these high temperature, high performance die materials significantly increased the mold life making possible the die-casting of copper and other high melting point materials. It is anticipated that a mold set incorporating a combination of nickel-base alloys and refractory alloys in the hottest portions will allow economical production of die-cast copper rotors.

Present plans entail the completion of the Inconel 617 and 625 long-run testing to demonstrate long-die-life-in-service, demonstrating the mold material and processing economic viability, and Phase II, namely die-casting several copper rotor designs for testing and analysis by the electric motor manufacturers. After which, the emphasis for this project will be to transfer this new die-casting technology to the manufacturers of electric motors.

Emphasis for this project will be to transfer this new die casting technology to the manufacturers of electric motors. Fabrication of prototype rotor die-casting for the largest motor manufacturers would expedite the transition to copper rotor motors. A meeting will initially be held with the electric motor manufacturers in order to announce the program. After which, the plan is to transfer technology to each electric motor manufacturer through demonstration of the die casting process.