Materials & Modifications to Die Cast the Copper Conductors of the Induction Motor Rotor

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Articles on materials appearing in materials issues have generally focused on the common aluminum-, zinc- and magnesium-based die casting alloys. This report differs in that it deals with pressure die casting of a relatively high melting metal, pure copper. Short mold life is the limiting factor in achieving a cost effective die casting operation for high melting metals and alloys. This study, where the primary objective was a more efficient induction motor via a copper-containing rotor, was forced to address the mold or die material issue. Generalizations about the properties of mold materials and modifications to the thermal environment of the die set necessary to achieve cost effective mold life in service were concluded from this study. Properties of the cast copper in the rotor structure and the performance of the cast copper rotor in motor tests are also reported.

Advantages of the Cast Copper Rotor

An exploded view of a typical motor is shown in figure 1. The rotor structure in the center consists of a stack of punched circular magnetic steel laminations interconnected with a "squirrel cage" structure of conductor bars with shorting rings at each end. Figure 2 is a photograph of an aluminum squirrel cage after dissolution of the iron. This structure has long been aluminum because of aluminum's high electrical conductivity and the ability to mass produce the rotor by pressure die casting the aluminum into the stack of steel laminations. Die casting, of course, is widely recognized as a low cost manufacturing process for large production volumes.

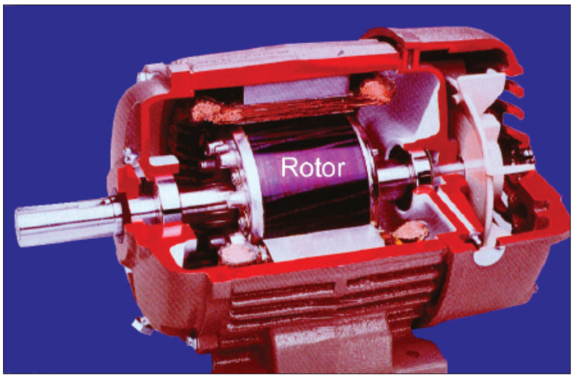

Fig. 1 – *Exploded view of typical induction motor. The die cast aluminum end ring with cast fan blades is visible on the rotor. The mulitple conductor bars connecting the end rings are contained within the iron laminations.*

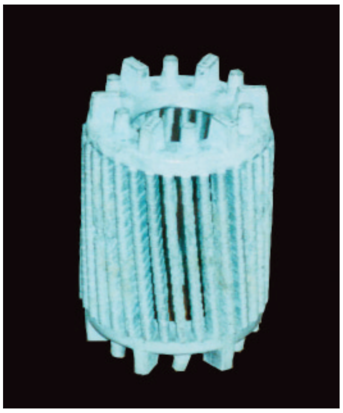

Fig. 2 – *The aluminum "squirrel cage" of a small motor rotor. The iron laminations have been removed by dissolution in nitric acid.*

Motor manufacturers have long realized that replacing the aluminum conductor structure of the rotor with pure copper would very significantly increase the electrical energy efficiency of the motor. Motor modeling had shown that motors with copper-containing rotors would yield overall loss reductions from 15 percent to 20 percent compared to the aluminum counterpart. For this reason, some special purpose motors and many very large motors (above about 250 Hp) are built with copper rotor structures by a costly and slow fabrication process. The potential total energy savings in applying copper to the rotors of medium horsepower motors are a significant national consideration. This is because, as reported by the U.S. Department of Energy, motors above 1/6 Hp use about 60 percent of all electricity generated in the United States. Medium horsepower motors in the 1 to 125 Hp range use about 60 percent of the electricity supplied to all motors. Because of the proliferation of electric motors in this horsepower range, a 1 percent increase in motor efficiency would save 20 billion kWhrs per year or 1.4 billion dollars in electricity (at 7 cents per kWhr).

As every die caster knows, tool steel molds used for the aluminum die casting process are entirely inadequate when casting higher melting point metals including copper (copper melts at 1083°C, aluminum at 660°C). Clearly, a durable and cost effective mold material is required for the manufacture of the cast copper rotor. Mold life measured in thousands of casting cycles must be achieved for the cast copper rotor to be economically feasible. To attack this problem, CDA assembled a consortium of companies including several major motor manufacturers. Funding was largely from the world copper industry through the International Copper Association with participation by the Air Conditioning and Refrigeration Technical Institute. Formcast, Inc. in Denver, CO provided the die casting expertise and the Buhler 750 ton horizontal real-time, computer-shot-controlled die casting machine for the trials.

The U.S. Department of Energy (DOE), and Office of Industrial Technologies (OIT), provided a NICE^3 grant to Trex Enterprises, San Diego, CA, an industrial partner at the inception of the project. This NICE^3 grant, early in the program, was an important catalyst for this successful development. These initial efforts and funding brought together the multi-disciplinary team of motor manufacturers, die casting equipment manufacturers, CDA/ICA technical expertise and Trex high temperature design and materials capabilities. Important equipment, die design and processing/handling variables were jointly developed; these guided the program through testing activities. Important computer analyses of heat transfer to the die casting molds (thermal modeling) was done in this early phase. This work guided the design of test dies and the selection of candidate mold materials, and created the basis for the design of the master die and die inserts utilized for the copper rotor die casting.

Candidate Mold Materials

Mold failures, in attempting to die cast high melting metals, result from thermal shock and thermal fatigue due to the temperature differential between the mold surface and cooler interior. Failures can be very rapid. The high melting temperature, high heat of fusion, substantial latent heat and high thermal conductivity of copper all combine to maximize these failure mechanisms. The ΔT between the surface and interior could be reduced by preheating the die inserts and by operating the dies at higher temperature. Mold materials that maintain strength on prolonged exposure to elevated temperatures would then be a necessity. A list of high temperature materials having thermal and thermoelastic properties conducive to minimizing thermally induced strain was assembled.

Studies done some years ago by the International Copper Research Association had identified tungsten and molybdenum as good candidates for copper die casting. That work was extended here. Molds machined from the molybdenum-based alloy TZM and the tungsten alloy Anviloy were tested. A variety of nickel-based alloys and superalloys suggest themselves. The nickel-base alloys do not have the low expansion coefficient of tungsten or molybdenum, but they offer high temperature strength and excellent cyclic oxidation resistance. An alloy with known excellent high temperature strength retention, the dispersion-strengthened INCONEL alloy 754 was selected. Other nickel-base alloys, INCONEL alloys 601,617, 625 and 718, having a range of thermoelastic properties in the anticipated thermal cycling range, were also included in the test program.

An H-13 tool steel die set was also fabricated to provide a baseline for comparison with the performance of high temperature mold materials. Compositions of the candidate mold materials are listed in table 1 and selected mechanical properties in table 2.

Test Molds and Melting Equipment

Because of the large amount of copper and the tremendous expense of iron lamination stacks for thousands of test shots, it was not practical to cast motor rotors in the mold material evaluation phase of the project. For this phase of the project, a test mold to simulate the action at one gate of a motor rotor mold was designed. This produced a two- pound flat semi-circular casting and required eight pounds of liquid copper in the shot sleeve. The test casting, gate section, runner and remaining shot sleeve biscuit are shown in figure 3.

This test mold consisted of six die inserts set into the steel master mold plates of the machine. A detailed drawing of the test mold is shown in figure 4. As experience was gained with this design, it was realized that two or three similar materials could be evaluated simultaneously using the several inserts, although admittedly, thermal and flow conditions were not identical at each of the six inserts. But simultaneous testing of materials significantly reduced the machine time required, and the amount of copper required for the mold material evaluation. This test mold design is an aggressive test exceeding the conditions that the rotor die set will experience and proved to be an

Anviloy 1200	
W	90
Ni	4
Fe	2
Mo	4

TZM Molybdenum	
Ti	0.5
Zr	0.09
C	0.025
O	0.025 max
H	0.005 max
Mo	99.25 min

Nickel-base alloys									
	Ni	Cr	Al	Ti	Co	Mo	C	Nb	Fe
INCONEL alloy 601	60.5	23	1.35	—	—	—	—	—	—
INCONEL alloy 617	44.5 min	22	1.15	—	12.5	9	0.1	—	—
INCONEL alloy 625	58 min	21.5	0.4 max	—	1.0 max	9	0.1 max	3.65	5 max
INCONEL alloy 718	70 min	15.5	0.7	2.5	1.0 max	—	0.08 max	0.95	7
INCONEL alloy 754*	78	20	0.3	0.5	—	—	0.05	—	1

* also contains 0.6 Yitria

Table 1 – *Nominal compositions of candidate mold alloys (wt%).*

	T(°C)	T.S.(1000 psi)	Y.S.(1000 psi)	El.(%)
Anviloy 1200	RT	150	140	2.0
	650	126	-	1.0
	1095	34.6	-	3.5
TZM 31/2” to 41/2” stress relieved bar	RT	80.0	70.0	5.0
INCONEL alloy 601 Hot finished plate ann.	RT	112	65	40
	650	70	45	33
	1177	4	2.1	14
INCONEL alloy 617 Solution annealed	RT	100	50	65
	650	82	33	53
	1177	6.9	4.9	59
INCONEL alloy 625	RT	130	65	50
	650	110	45	55
INCONEL alloy 718 Hot rolled 4” round annealed and aged	RT	197	164	17
	650	192	165	19
INCONEL alloy MA 754 Annealed bar	RT	140	82	20
	650	82	50	22
	1177	16.7	16	15

Table 2 – *Selected mechanical properties of candidate mold alloys.*

excellent test for quickly comparing and ranking the various mold materials.

A suitable approach to melting significant quantities of high purity copper and providing a means to safely deliver molten copper to the shot sleeve required consideration. Aluminum is generally melted in a large gas fired furnace and transferred from the holding furnace to the shot sleeve by ladle or mechanized transfer device. This approach was deemed inappropriate for copper because the substantial heat from a large volume of molten copper would present difficult working conditions for the operators and because molten copper picks up oxygen rapidly. Protecting the melt would be expensive and difficult. The solution was to individually induction melt sufficient copper for each shot with an Inductotherm power supply sized to melt the charge in two minutes: i.e. within the time required for one complete cycle of the machine. (Motor manufacturers die cast aluminum rotors for motors of the size planned for this project in about two minutes). This required a 60 kW power supply for the eight-pound charge. Use of two furnaces alternately switched to the supply allowed maximum utilization of the power source. Individual charges were conveniently handled and weighed by using chopped copper wire rod. The metal was melted and heated to about 1230°C providing about 150°C of superheat.

As noted earlier, operating the mold at higher temperatures minimizes the mold surface strain on each casting cycle and the resulting thermal fatigue or “heat checking.” This is an absolute necessity to avoid cracking on the first shot of the tungsten and molybdenum alloy mold candidates because of the high ductile-to-brittle transition temperatures of these materials. Thermal modeling of the mold showed that temperatures above about 550°C for the molybdenum and tungsten alloys would result in thermal cycles with resulting maximum stresses below the yield points of these materials. Because of the lower thermal conductivity of the nickel-base alloys, it was estimated that this critical temperature would be about 625°C for these alloys. These temperatures

Fig. 3 – *Test casting used to evaluate and compare candidate mold materials. A two pound copper biscuit is above the gate area and runner bar.*

are well in excess of the capability of the hot oil heaters normally used to increase mold temperatures. A variety of configurations of electric resistance heaters inserted into both the moving and stationary die inserts and into the cavity die holders were tried. To minimize heat loss to the machine and to achieve higher insert temperatures, a NASA-developed high R insulation layer was placed behind the inserts for the last runs. The oil circulation channels in the master mold assembly served to prevent overheating of these components. Prior to a run, the die inserts in position on the machine were preheated by an oxy-acetylene torch and in later runs by the array of electrical resistance heaters. The rate of heat transfer and resulting thermal shock from contact with molten copper was to some extent controlled also by the use of a dry mold release system sprayed on the die insert surfaces prior to each shot.

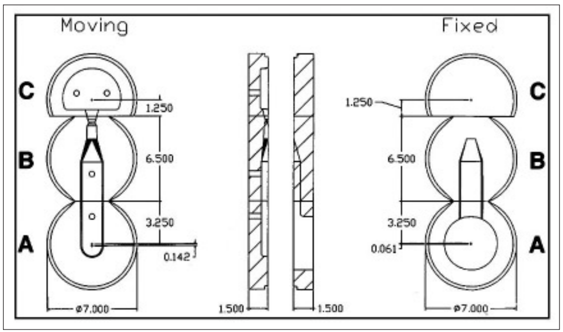

Fig. 4 – *Detail of the die inserts for the test castings. This design allowed for more than one alloy to be simultaneously evaluated.*

Die Material Test Results

H-13 Tool Steel

An extended run using H-13 tool steel die inserts for the single gate test mold was conducted to establish a performance baseline. Eight-pound copper charges were induction melted and fed directly to the shot sleeve. The die inserts were preheated by the torch to about 350°C. Substantial visible damage was evident after about 20 shots. The H-13 inserts deteriorated steadily by heat checking and cracking in succeeding shots. Over 750 castings were produced, however before flash in the heat check cracks, especially at the joints between the insert sections, (see figure 4) due to erosion became so large so as to make ejection difficult.

These test castings provided an opportunity to assess the quality of die cast copper. The gate and runner macrostructures showed an outer columnar chill zone and a mixture of smaller and larger equiaxed grain structure in the bulk. A small volume fraction of interdendridic eutectic copper-oxygen phase and slag type inclusions were also present, but the overall microstructure was sound (see figure 5). Surface cracks and small tears were evident in the gate. As expected with a die casting, a small amount of microporosity was found. Chemical analysis showed oxygen levels from 0.06 to 0.15 percent and iron from 10 to 350 ppm. The iron comes from the iron alloys of the shot sleeve, runner and test cavity inserts. Erosion and inclusion of iron or oxide particles apparently leads to the wide variation in iron content. The cumulative impact of the inclusions, microporosity and iron contamination on electrical conductivity was minimal, however. Electrical conductivity measurements taken from the test castings averaged 98 percent IACS and varied between 95 and 101percent IACS. This is the critical property in the motor rotor application.

TZM and Anviloy

Components of the test die insert set of figure 4 were machined from these molybdenum and tungsten alloys and arranged for simultaneous testing in an extended run. The die set was preheated by electrical resistance heaters to about 450°C and maintained at this temperature during the run by the heat from the copper supplemented by the resistance heaters. This was the maximum temperature attainable with the heater array design at the time and was about 100°C below the minimum required to avoid exceeding the yield strength at the surface suggested by the thermal modeling. Over 500 shots consuming two tons of copper were cast. No heat checking of either alloy was evident but minor cracking of the Anviloy inserts at the sharper radii was noted. A second run was carried out some weeks later extending the total number of shots to 940. At this point, both the TZM and Anviloy inserts showed additional minor cracking at the ejector pin holes due to inadequate allowance for the higher thermal expansion of the steel ejector pins. Otherwise these die sets appeared to be capable of extended runs in this severe copper die casting exercise with no heat checking in the gate areas, contours and flat surfaces. The TZM inserts did suffer serious surface

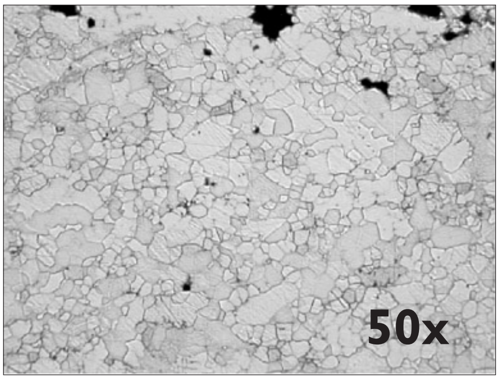

Fig. 5 – *Microstructure of die cast copper specimen from the gate area of a casting produced in the H-13 tool steel die set.*

degradation by oxidation because the surface reached temperatures above 650 to 700°C where the oxide melts and volatilizes. This problem makes TZM a poor choice for copper die casting. It appears that with sufficient preheat and maintenance of operating temperature at 550°C, Anviloy is a suitable mold material for copper die casting. High base material and fabricating costs are the remaining deterrents to the use of this tungsten alloy, but it may offer a viable alternative for use in a part or parts of the mold such as the runner where the incoming metal temperature and flow rate are extreme.

The photograph of figure 6 shows the TZM and Anviloy die inserts and mounting plate after 500 shots. The resistance heaters, thermocouple leads and cooling lines can be seen.

Nickel-Base Alloys

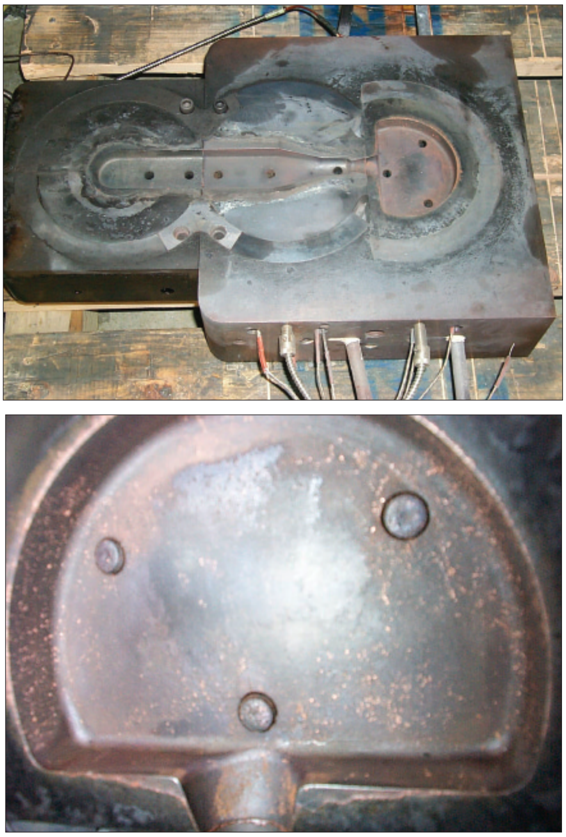

Fig. 6 – *Top: Moving half TZM and Anviloy die inserts after 940 shots. TZM is in the bottom (left) position and Anviloy in the middle and upper positions. Electrical resistance heaters and thermocouple leads are visible on the lower edge of the mounting plate. Bottom: Close-up of Anviloy die inserts after 500 shoots.*

Three INCONEL alloys, 617, 718 and 754, were evaluated in an extended run using the test mold set up. Two inserts of each alloy were arranged in the six-insert configuration (see figure 4). In a run of 250 shots, the die inserts were preheated to 350°C using electrical resistance heaters. The temperature was not permitted to fall below 350°C in the cooling portion of the shot cycle. The INCONEL alloy 754 inserts began cracking in less than 50 shots. This was somewhat surprising at the time, as this alloy exhibits the highest strength at the copper melting temperature. But this alloy also has rather low ductility at elevated temperatures. INCONEL alloy 718 began cracking at about 100 shots. Being a precipitation-hardening alloy, alloy 718 has very low strength at the melting point of copper, but very high tensile and yield values at the interior mold operating temperature and only fair ductility over the entire range of temperature. The best performing alloy was INCONEL alloy 617 showing only minor craze cracking after 250 shots at this low operating temperature. The conclusion is that the solid solution strengthened INCONEL alloy 617 has the best combination of strength and ductility in the operating temperature range for copper die casting. High fracture toughness at service temperature is apparently an important criterion for high temperature die casting mold materials.

In a second extended run to evaluate solid solution strengthened nickel-base mold alloys, Inconel alloys 601, 617 and 625 were machined to die inserts. In order to heat and maintain the high die insert operating temperatures found to be critical to improved die life, the die inserts and cavity holders were drilled to position two 1 kW resistance heaters in each insert and four in each steel cavity holder. NASA-developed-high R insulation was placed behind the insert to reduce heat loss to the machine. This allowed the preheat and minimum operating temperature to be increased first to 540°C and later to the 625-640°C range. As the operating temperature was increased, the amount of heat checking was markedly reduced. Finally, in the last 330 shots at the highest operating temperature, there was minimal additional deterioration in this die set. A total of 950 shots at the several progressively increasing operating temperatures had been made in this rather severe test. A protective oxide film was formed and retained on the alloy surfaces. These three alloys are known to have excellent cyclic oxidation resistance.

Chemical analysis of several copper test castings showed average iron pick up of 65 ppm, 5 ppm nickel and 0.074 wt percent oxygen. The microstructures were very similar to that of figure 5 and basically sound. The electrical conductivity was higher than that of the castings from the H-13 alloy die sets averaging 99.9 percent IACS.

Conclusions from Die Material Tests

These tests indicate that the INCONEL alloys, 601, 617 and 625 operated in the 600-650°C temperature range are very promising mold materials for die casting of copper motor rotors. In the 950 shots with these three alloys in different positions in the test configuration, clear distinctions between these three alloys were difficult to discern. Alloy 601 may have somewhat inadequate tensile and rupture strengths for very long campaigns at 650°C and above.

An important conclusion from this work is that it is absolutely essential to operate 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 expansion and contraction associated with each cycle and thus minimizes thermal fatigue of the surface that leads to crazing and eventually to significant cracking. INCONEL alloys 617 and 625 operated at about 650°C are excellent die materials. Temperatures above 650°C are not required and in fact would reduce productivity by increasing the cooling time. A practical method to achieve the necessary die temperature has been developed.

These tests are also encouraging in terms of the purity and high conductivity of the runner scrap produced in the nickel alloy molds with a steel shot sleeve. This will allow remelting of scrap at the die casting facility or sale of the scrap at or near electrical grade copper prices.

Rotor Die Casting Trials

Tooling, Melting and Machine Considerations

Copper motor rotors were pressure die cast and evaluated in motor tests by the several motor manufacturer partners in Phase II of this project. A new two-position induction furnace was designed and built by Inductotherm to enlarge the melt capacity to 40 pounds of copper. The 60 kW power supply was used in the rotor casting trials, but resulted in longer melting times than desirable. Had a larger power supply been available, melt times and total cycle times could have been reduced to the 2 to 2.5 minutes typically seen in casting aluminum rotors of the 15 Hp size investigated here. An appropriate three-platen master mold set was obtained from Buhler in Switzerland. Tooling for these rotor casting trials were designed by DieTec GmbH, Gossau, Switzerland. The end ring die inserts are in the stationary and moving platens and the iron laminations are mounted on a steel mandrel in a split alloy cylinder insert in the center platen. Lamination stacks supplied by the motor companies were assembled and compressed on the mandrels. A cast copper rotor in the ejection phase of the cycle is shown in figure 7.

The initial casting run utilized an existing steel rotor die set of an outmoded motor, but served to establish a casting process for rotors. The very first shots failed to fill the end ring at the far end of the nine-inch long stack due to heat loss in the cold (room temperature) shot sleeve. A heated shot sleeve surrounded with a thermal wrap with a replaceable center insert at the point of pouring, was designed and installed. Heat was provided by both preheating with a gas torch at the pour opening and by an array of electrical resistance heaters surrounding the sleeve. These new shot sleeves were specifically sized for rotors to be cast in order to avoid air entrapment and resulting porosity in the cast copper.

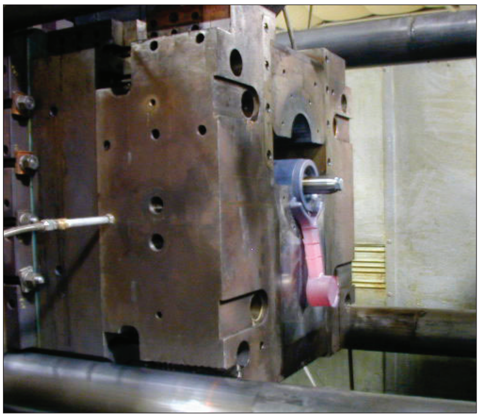

Fig. 7 – *Die cast copper rotor about to be ejected from the center platen portion of the 750 ton machine.*

Rotors were cast for four motor companies. At this writing, motor performance measurements had been completed by two companies. The first rotors were for a 15 Hp motor and were 5.7 inches in diameter with a six-inch stack height containing 14 pounds of copper in the conductor bars and end rings. This required a 29-pound charge of molten copper to the shot sleeve. The second set of rotors were larger, being 6.5 inches in diameter with a stack height of 9.5 inches containing 25 pounds of copper requiring melting of 39 pounds of copper per shot.

Because only a small number of test rotors were to be cast for evaluation by these two manufacturers, available H-13 die inserts were used. These were preheated and heated between shots by means of a gas torch in the shot sleeve to minimize thermal shock and heat checking. Longer runs in the future will use INCONEL alloy tooling and appropriately mounted electrical resistance heaters as taught in the mold material study phase of this project. A schematic illustration of the die inserts equipped with electrical resistance heaters and backed with insulation to be used in future production runs is shown figure 8.

The real-time shot control capability of the Buhler machine provided opportunity to study a number of die casting variables that might be expected to affect the quality of the cast copper and the performance of the die cast copper rotors in motor tests. On this machine, ram speed can be set at a number of ram positions and the final compacting pressure and duration is adjustable. This machine allows independent control of die closure and shot sleeve velocities and pressures providing accurate and replicable machine settings for each shot.

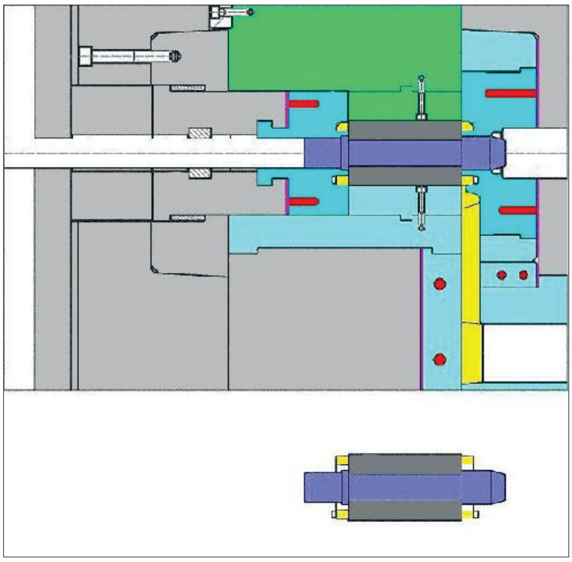

Fig. 8 – *Horizontal pressure die caster with tooling for rotor casting in closed position. The arbor (dark blue) and the steel rotor laminations (dark gray) are shown in the insert and in position in the machine. Copper from the shot sleeve biscuit, runner bar and end rings is shown in yellow. The nickel alloy end ring inserts are shown in medium blue with electrical resistance heater elements in red. These are backed with insulation (pink) as are the runner inserts which would be nickel alloy or tungsten. Red circles here indicate heater positions. The moveable slide to allow insertion and removal of the rotor is shown in green. Ordinary steel backing plates of the master mold set are shown in light gray. (Courtesy of DieTec, GmbH)*

Basically the machine was set to a low ram speed of about 0.25 m/s to pass the pour opening, increased to 0.3 to 0.5 m/s to fill the shot sleeve, increased at this point to fill the runner, increased again to advance the molten metal front through or somewhat past the gates and finally increased to fill the near end ring, conductor bars and far end ring. Ram positions and velocities after filling the shot sleeve were considered to be potentially of significance as was the final ram pressure. The ram speed during rotor fill was varied from 0.8 to as high as 3 m/s. Ram position at the point of rotor fill was varied to attempt to fill the conductor bars evenly, or at the other extreme, to have the lower bars fill first and fill the far end ring from the bottom and begin to fill the upper conductor bars from the back. This would lead to a joining of solidification fronts on these conductor bars that might reduce their conductivity.

Ram pressure after completely filling the rotor cavity was varied from about 11,750 psi to a lower value of about 5,150 psi. The compaction time was adjusted to be long enough to ensure that the end rings were cooled to below red heat (about 600°C) and the conductor bars were cool enough to maintain the compression of the iron laminations.

Because copper is so much hotter than aluminum entering the conductor bar channels, there was some concern that the conductor bar would weld to the iron laminations or that the properties of the iron would be compromised by heat treatment. Welding of laminations to the copper conductors would defeat the purpose of the oxide insulation on the laminations and increase the magnetic loss component of total motor losses. On ejection from the machine, half of the rotors were water quenched to rapidly shrink the copper from the iron as a means to prevent this problem and to minimize a high temperature anneal of the iron. The other half was air cooled.

Structure and Chemistry of the Cast Copper

Metallurgical examination of cast copper rotors confirmed that there was no interaction between the copper conductor bars and the iron laminations. The conductor bars showed small defects at the copper-iron interface and lamilar defects in the copper resembling intergranular cracks and cold folds due to micro-shrinkage and entrapped inclusions, although these copper defects were not numerous. Chemical analysis revealed that small amounts of iron (10 to 11 ppm) and oxygen 0.084 to 0.163 wt. percent were picked up during casting. The combined effects of the presence of microstructural defects and chemical contamination reduced the electrical conductivity of the cast copper conductor bars to 96.8 percent and 98.7 percent IACS in the two measurements performed on the first set of rotors cast.

Porosity in the far end ring of the first set of copper rotors appeared to be 2 percent to 3 percent but did not extend into the conductor bars; no balancing to compensate for uneven weight distribution was required. The larger rotors of the second group cast were more of a problem in this regard showing as much as 25 percent voids in the first shots and 8 percent to 10 percent in the rotors tested for electrical performance. This is apparently due to inadequate venting at the far end ring and excessive oxygen pick-up during the very long melting time (about 13 min.) resulting from the small power supply available. As discussed below, this porosity had little apparent effect on the performance of these copper rotors. Die cast aluminum rotors very often have considerable porosity requiring use of extra aluminum to compensate for porosity and always require balancing.

A surprising conclusion from the study of machine casting variables was the remarkable insensitivity of the process to ram positions and corresponding velocities and final pressure. Rotors cast at the wide range of settings noted were essentially indistinguishable both structurally and in terms of electrical performance in motor tests. This conclusion extends to rotors cast with machine variables set to mimic a simple hydraulic horizontal pressure die casting machine similar to machines found in many motor plants. From this it can be concluded that the process for pressure die casting copper motor rotors is demonstrably robust allowing a wide range of machine parameters. This may be attributable to the high heat of fusion of copper allowing filling of the rotor cavity over a broad range of speed. An important caveat is that the nickel-base or tungsten alloy tooling must be preheated to and maintained at above 600°C to avoid premature die failure.

Motor Performance with Copper Rotors

Motor companies tested the copper rotors according to IEC 34-2 and IEEE Std. 112 Method B. A standard rotor with die cast aluminum bars and end rings was tested to provide the baseline. All rotors were tested by each company in the same wound stator dynamometer test bench to eliminate other performance variations.

Seven of the smaller copper rotors from the first group cast over a range of machine parameters showed very little variation in the numerous electrical parameters measured. The overall motor losses (sum of five measured losses) were 14 percent lower in the copper rotors compared to the aluminum. Full load losses in the rotor were about 40 percent lower than that of the aluminum. It is important to note that the improvements in motor performance by substituting copper for aluminum in this rotor were made without optimizing the slot design nor the overall design of the motor for the copper. Laminations for a standard (aluminum) rotor were used in this work. Additional improvements in efficiency by as much as 5 percent to 10 percent reduction in losses are expected through rotor and overall motor design optimization.

These motor tests showed that there also was no difference in performance of water quenched vs. air cooled rotors. Although the post-casting cooling method had no effect on the results, water quenching reduced handling time to one minute compared to a 20 minute air cool. This would be important to manufacturing efficiency.

Motor tests of the second set of larger rotors cast showed even more dramatic results. This is, in part, due to the use of a rotor lamination slot design specifically designed for copper. A cross-section of this cast copper rotor is shown in figure 9. The manufacturer provided sufficient laminations for 14 rotors. Again, there was remarkable consistency in the results for the four rotors tested and compared to the same motor with an aluminum rotor. The rotor losses were 40 percent lower in the copper rotors and the overall losses were reduced by 23 percent. Lower losses led to reduced rotor and stator winding temperatures. On completion of testing, the temperature of the stator winding of the motor with the copper rotor was 32°C cooler than the aluminum; the copper rotor was 29°C cooler than the aluminum rotor. Lower temperatures mean that smaller internal cooling fans can be employed and this had a significant effect in reducing the parasitic component of the friction and windage losses. Motor temperatures translate directly to motor life and maintenance costs. As a general rule, insulation life is doubled

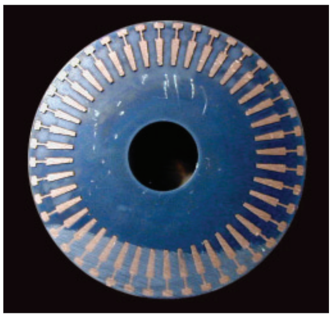

Fig. 9 – *Cross-section of rotor showing copper filling the slot openings by the pressure.*

for every 10°C decrease in motor operating temperature. Motors with cast copper rotors, with proper maintenance, will last longer and will be more reliable.

Overall motor efficiency was increased by a solid 1.2 and 1.6 percentage point in motors tested with the two sets of copper rotors cast. This is significant because 20 years of motor efficiency improvements have been accomplished by using all of the readily available approaches. Copper rotors represent the only way to reduce losses significantly without turning to expensive amorphous iron or superconductivity.