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Use Of High Temperature Die Material & Hot Dies For High Pressure Die Casting Pure Copper & Copper Alloys

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Abstract

Little use has been made of pressure die casting for the manufacture of copper or copper alloy parts due in large part to poor economics resulting from short die life in casting these high melting metals. A research program initiated in 1997 was driven by the promise of a significant increase in the energy efficiency of the induction motor by substituting high conductivity copper for aluminum in the rotor "squirrel cage" structure. Use of high temperature materials including tungsten-, molybdenum- and nickel-base alloys was examined in an extensive series of casting trials. The importance of operating dies at elevated temperatures to minimize the cyclic temperature gradient through the die that leads to heat checking and cracking has been demonstrated by both thermal modeling and experimentation. Shot-by-shot induction melting of the copper charge has been implemented and is described. Performance of motors with die cast copper rotors is compared to that of the aluminum rotor. Preliminary work on the applicability of the hot high temperature die technology combined with semi-solid processing for copper alloy part production is presented.

Introduction

The work described in this paper on die casting of copper was driven by the objective of achieving a significant increase in the electrical energy efficiency of the induction motor by substituting copper for the aluminum in the squirrel cage structure of the motor rotor. This efficiency increase is due in large part to the reduced I2R losses in the rotor because the electrical conductivity of copper is nearly 60 percent higher than that of aluminum. Motors with copper rotors are expected to show overall loss reductions of 15 percent to 20 percent compared to the aluminum counterpart rotor. Because of the proliferation of motors, a very significant energy savings is possible. The U.S. Department of Energy[1] reports that motors above 1/6 Hp use about 60 percent of all electricity generated in the United States and that medium power motors (1 to 125 Hp) use about 60 percent of electricity supplied to all motors. A 1 percent increase in motor electrical energy efficiency would save 20 billion kW-hrs per year or $1.4 billion in electricity (at 7 cents per kW-hr) and 3.5 million barrels of oil in the U.S. These savings would be multiplied by about a factor of four on a worldwide basis.

Although very large motors (>250 Hp) are equipped with copper rotors manufactured by expensive and time consuming fabrication procedures, pressure die casting is the only practical way to produce the huge numbers of integral horsepower motors used in our industrialized society. Figure 1 shows a typical rotor made up of a stack of iron laminations with the end rings of the rotor visible. An aluminum squirrel cage of a similar motor liberated from the rotor by dissolution of the iron in acid is also shown.

Figure 1

Although motor manufacturers have long recognized the value of using electrical grade copper in the rotor, the poor manufacturing economics of die casting copper has been an impenetrable barrier. The high melting point of copper (1982°F, 1083°C) results in very rapid deterioration of tool steel dies. The principle failure mechanism is referred to as "heat checking" by die casters, but decarburization and softening of the steel at the high surface temperature are also contributors.[2] Heat checking is a thermal fatigue phenomenon resulting from the rapid cyclic expansion of the die surface layer on contact with molten metal and the constraint of the surface by the much cooler inner portions of the die. Cooling of the outer layer on each cycle to a temperature below that of the bulk of the die puts the surface under a large tensile stress that can exceed the yield point of the die material. This surface-to-interior differential expansion and contraction is greatly exacerbated in die casting high-melting metals such as pure copper, its alloys or a stainless steel compared to the aluminum-, zinc- and magnesium-based alloys commonly die cast. Clearly, much improved die life must be achieved for the copper rotor to be practical. This meant that a principle objective of this work was necessary to identify suitable high temperature die materials. Consideration of the thermal fatigue failure mechanism suggests that the surface-to-interior ΔT and resulting large strains can be minimized by raising the temperature of the bulk of the die insert. Herman et al[3] in 1975 and Doehler[4] in 1951 made this same suggestion. A second objective of the development effort was to devise and demonstrate a practical system for heating and insulating the die inserts to maintain the high temperature critical to improving die life. A thermal modeling exercise as part of this work allowed determination of the minimum temperature necessary to avoid stresses exceeding the material yield stress for the case of tungsten. This paper presents a detailed account of the work introduced in earlier publications.[5,6]

Experimental Method

Material Test Die

Evaluations of candidate high temperature die materials were done in the test die shown in figure 2. Casting of full motor rotors involving the expense of thousands of lamination stacks, large amounts of copper and the difficulties of manually handling heavy rotors in large numbers in a developmental die casting facility ruled against rotors as the die material test vehicle. The test die used consists of six machined inserts. This configuration allowed use of readily obtainable pieces of alloys and provided for evaluation of two or even three materials simultaneously saving considerable time and expense in obtaining a preliminary reading of the suitability of a material for copper die casting. The gate area was designed to simulate a single gate of a multiple gate rotor die. Anticipating casting rotors for motors on the order of 15 Hp for motor companies later in the project, this gate represented one of eight accommodating the feed of 2 lbs of copper to the flat semi-circle at the top of the casting. Eight pounds of molten copper is fed to the shot sleeve to produce the semi-circular section, gate section, runner and remaining biscuit. A dry powdered release agent was applied immediately before each shot. The test die design is believed to be an aggressive test of die materials exceeding conditions the rotor die set experiences.

Figure 2

Copper Melting Facility

Where aluminum is normally melted in gas-fired furnaces and often held in large holding units for distribution of molten metal to one or several machines, this approach was not thought to be suitable for copper. Control of oxygen and hydrogen in large furnaces holding molten copper, although possible with good practice and experienced melters, would be difficult. For this work, chopped wire rod (C11000 copper) was melted. This provided the proper oxygen and otherwise high purity required and was a convenient size for weighing out individual charges. Charges were melted by induction on a shot-by-shot basis. The target was a two-minute cycle for the material test die consistent with the manufacturing rates for aluminum rotors in the size range planned for casting in Phase II of this project. This required a 60 kW power supply. Maximum utilization of the power supply was achieved by using two push-up furnaces alternatively switched to the supply.

As shown below, this worked well for the 8 lb test die shots. In the rotor casting phase of the project, where rotors as large as 25 Hp requiring 39 lbs of molten copper to the shot sleeve were cast, melt times were increased to as long as 13 minutes using the available 60 kW power supply. Oxygen pick-up was experienced resulting in brittle rotor structures in one short casting campaign. Adjustment of the size of the power supply would avoid this difficulty. Another approach now under active consideration for a motor die casting plant is the use of electrical grade copper in a closed induction melting furnace under inert gas cover. Charges would be poured to the shot sleeve by pressurizing the melt chamber similar to operation of a low pressure die casting machine.

The shot sleeves used in this work were H13 steel. Nickel-base alloy shot sleeves would reduce iron pick-up and are recommended for production. To maintain super heat of the copper, the shot sleeve was preheated with an oxy-acetylene torch. Later for die casting rotors, an electric resistance heated shot sleeve surrounded with a thermal wrap was put into service. This design had a replaceable center insert at the point of pouring. Shot sleeves were specifically sized for rotors to be cast to minimize air entrapment and to minimize porosity in the copper structure.

Real-time Shot Control

The 660 metric ton Buhler machine at Formcast Development, Inc. used for this study was equipped with real-time shot control. This capability 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 are adjustable.

For the die material trials, the ram speed during die fill was 1 m/s (3.28 ft/s) and the final pressure was 7050 psi. For copper rotor casting, basically the machine was set to a low ram speed of about 0.25 m/s (0.82 ft/s) to pass the pour opening, increased to 0.3 to 0.5 m/s (1 to 1.6 ft/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 velocity after filling the shot sleeve was considered to be potentially significant as was the final ram pressure. The ram speed during rotor fill was varied from 0.8 to as high as 3 m/s (2.6 to 9.8 ft/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, 1112°F) and that the conductor bars were cool enough to maintain the compression of the iron laminations.

Post-Casting Cooling of Rotors

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 of the laminations and increase the magnetic loss component of total motor losses. On ejection from the machine, half of the rotors were water quenched in an attempt 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.

3-D Computer Analysis of Die Thermal Profiles

A 3-D computer analysis of heat transfer in the die material test inserts vividly showed the thermal gradients generated when the die is brought into contact with molten copper (K.D.Williams, Flow Simulation Services, Albuquerque, NM). This analysis was valuable in understanding the thermal fatigue failure mechanism and how to minimize or largely avoid it. The time to gate freezing and the number of shots to reach the equilibrium temperature profile were also obtained.

Temperature profiles in H13 die inserts were generated for this material in the test die geometry of figure 2. Die surface temperature distributions at the instant of filling with 1200°C (2192°F) molten copper and at points in time immediately thereafter were calculated. Since the die surfaces are generally coated with a mold release compound, a value for the heat resistance, R, of this coating had to be selected. This was taken as 1°C cm^2/watt, a value in the middle of the range found in the die casting literature. Figure 3a shows the result from this model for the mold surface temperature distribution immediately after filling of the die. In this figure, to avoid representational problems, the die surface temperature has been "painted" onto the surface of the cast object. In this case the casting surface will actually be hotter than the die surface because of the surface heat conducting resistance. In fact, in this example, the investigators assumed that coating the narrow gate region would be difficult and assigned a very low heat flow resistance to this region. Thus, the die surface temperature in the gate region is essentially at the melting point of copper. This means that the surface of the gate region of the die insert has risen from the initial temperature of 200°C (392°F), by 880°C (1616°F). Because of the low thermal conductivity of H13 tool steel, the body of the mold is still at 200°C (392°F). This implies that the surface has a temperature-induced strain of a least 1.19 percent, an enormous strain to sustain on a cyclic basis.

Immediately after filling, the coated areas of the die surface are only in the range of 550°C-600°C (1022°F-1112°F), or 350°C (662°F) above the initial temperature and the bulk of the insert. The surface at the biscuit area at the end of the ram in the shot sleeve is at about 800°C -850°C (1472°F -1562°F).

At 0.5 seconds after casting, the temperature in the uncoated gate area has started to drop, but the rest of the die surface is getting hotter (see figure 3b). The metal volume in the gate is small and with R taken as a very small value in this region, heat diffusion to the die steel is rapid. The longer coated surface areas have risen to the 700°C to 800°C (1292°F to 1472°F) range. After 6.5 seconds (see figure 3c) the gate area is relatively cold but coated areas of the larger volume sections of the casting have risen to 750°C to 900°C (1382°F to 1652°F).

Figure 3

Thus, in the H13 tool steel, we expect from these calculations that the die surface temperature will rise to values ranging from 825°C (1517°F) to over 1000°C (1832°F) everywhere outside the gate region (assumed to be uncoated in this example). These high temperatures occur even with a surface coating with a resistance of 1°Ccm^2/watt over these surfaces. These high surface temperatures imply that substantial surface strain occurs everywhere in the H13 dies.

Figure 4a shows the solidified fraction of the cast copper at each point along the plane of symmetry of the casting at the instant that the mold is filled. Dark blue indicates that the copper is liquid or, at most, just a few percent solid. When the copper is the color corresponding to liquid in this figure, one cannot tell its actual temperature except to know that it is equal to or greater than the melting point of copper. The pale green in the upper section indicates that the cast copper is about 25 percent solid and 75 percent liquid, so the temperature is at the melting point of pure copper; i.e. 1083°C (1981°F). In fact, except for the dark blue areas in this cross section, all the copper is partially, but not completely solidified. Therefore, the entire local volume must be at the liquidus, the melting point in a pure metal.

Figure 4

Figure 4b shows the solidified fraction 0.53 seconds after injection was complete. The gate region is already 100 percent solid as are some regions near several of the walls. Elsewhere, the copper is at the melting point, only about 30 percent solid, with a large amount of residual heat of fusion to "give up" to the walls before it can cool below 1083°C (1981°F). It is this large amount of residual heat that will continue to heat the side walls to high temperatures after casting is over. This was shown at 6.5 seconds after casting in figure 3c.

This modeling method was used also to look at the effect of the oil and water cooling in the mold holders of the Buhler machine on the temperature distribution in the mold and the increase in overall mold temperature with the first few shots. In the first five shots, the wall temperature of the beginning of the shot of the H13 die rises from the initial value of 200°C (392°F), established by oil heating, to about 360°C (680°F). This turns out to be affected very little by placement of the cooling lines. Figure 5 shows the die temperature contours for the H13 test die after five cycles (just prior to the sixth shot).

Figure 5

It was clear that to achieve the higher average mold temperatures required to minimize the ΔT between the surface and interior associated with each cycle, and the resulting cyclic strain, it would be necessary to both insulate the die inserts from the backing steel and provide a source of heat directly to the inserts.

An example of the resulting surface temperature distribution on a tungsten die (as "painted" on the cast object) is shown in figure 6. Here, the initial wall temperature had been taken as 650°C (assuming direct die insert heating and insulation). Although the gate area surface temperature is near the melting point of copper, again because of the low surface resistance assumed for this region, the remaining surface temperature is now only in the range of 750°C to 800°C (1382°F to1472°F), only a 150°C (302°F) increase. The smaller increase compared to the H13 example is in part due to the higher thermal conductivity of tungsten.

Figure 6

Temperature-time profiles in a tungsten insert preheated to 380°C (716°F) are shown in figures 7 and 8 for thermocouple locations near the front, center and rear of the insert. Model predictions using a mold/copper contact resistance of 0.3°C cm^2/watt are shown in figure 7. Figure 8 shows the actual measured temperatures during the shot. The agreement is excellent. A ΔT of about 400°C (752°F) between the front and rear of the insert is generated immediately after filling the die cavity. Calculations showed that this would lead to a plastic strain on each cycle. For tungsten, the minimum die temperature to assure strain and resulting stress below the yield point is 550°C (1022°F). The ductile/brittle transition temperature at about 200°C (392°F) for tungsten is also indicated in figure 8. This means that the machine operator cannot use the first few shots to achieve the operating temperature without cracking the die.

Figure 7

Figure 8

In nickel-base alloy molds, the temperature gradient and resulting surface stress will be higher due to the lower thermal conductivity of these alloys. The minimum die temperature to assure that cyclic surface stresses remain below the yield point was estimated to be about 625°C (1157°F).

It is interesting to note that this modeling exercise also showed that pressure die casting of stainless steels would result in maximum die surface temperatures very similar to those seen here for copper even though the liquidus temperature is about 300°C (570°F) higher. The much lower thermal conductivity of stainless steels accounts for this. Die casting trials carried out at Formcast Development with a Type 316 stainless steel introduced to the shot sleeve at 1600°C (2900°F) using an H13 die set coated with a dry powder release agent have shown that production of 10 to 12 parts is feasible. The molten steel did no severe damage to the shot sleeve, plunger, die cavity or ejector system. Die life would be expected to be quite limited however. Die life could be substantially extended if the hot die technology developed in this work were utilized and would be further improved if the stainless steel were processed as a semi-solid metal. Work toward this end is proceeding as part of another project in which CDA is a participant.

Die Material Evaluation Tests

H13 Die Steel

An H13 die set was run to failure to establish a base line and to gain experience in die casting copper. To minimize thermal shock with the first few shots of molten copper, the dies and shot sleeve were preheated to about 350°C (662°F) with an oxy-acetylene torch. As expected, substantial physical damage was quickly evident after about 20 shots. The run was continued for a total of 750 shots during which steady deterioration by heat checking, cracking and erosion at insert joints and ejector holes was taking place. The run was discontinued when ejection of the casting became difficult as copper solidified in the deep fissures.

These test castings provided an opportunity to assess the quality of the die cast copper in the worst case scenario of all iron-base alloys in the shot sleeve, runner bar and test cavity inserts. Chemical analysis showed oxygen levels from 0.06 percent to 0.15 percent and iron from 10 to 350 ppm. Erosion and inclusion of iron oxide particles apparently leads to the wide variation in iron content. Electrical conductivity measurements averaged 98 percent IACS and varied between 95 and 101 percent IACS. This is the critical property for die cast copper in the motor rotor application. The gate and runner macrostructures showed an outer columnar chill zone and a mixture of small and larger equiaxed grain structure in the bulk. As is common in electrical grade coppers, a small volume fraction of interdendridic eutectic copper-oxygen phase and a few slag type inclusions were also present but the overall microstructure (see figure 9) was sound.

Figure 9

Surface cracks and small hot tears were evident in the gate area. As expected in a die casting, a small amount of microporosity was found. But the cumulative effect of defects and impurities did not degrade the electrical conductivity to an unacceptable level.

TZM and Anviloy

TZM is a molybdenum-base alloy containing nominally 0.5%Ti, 0.09%Zr and 0.025%C. Anviloy 1200 is tungsten-base containing 4%Ni, 2%Fe and 4%Mo. The alloys were tested simultaneously in the test die configuration of figure 2. At this point in the die material evaluation investigation, the first heated die configuration had been designed and installed on the machine. This allowed preheating and maintaining the dies at 450°C (842°F). This was the maximum temperature attainable with this initial heater array design and was about 100°C (212°F) below the minimum required to avoid exceeding the yield strength at the surface suggested by the thermal modeling. Failure of one or more heaters during the first run of 500 shots resulted in operation at an even lower temperature for a portion of the run. Despite these problems, no heat checking of either alloy was evident but minor cracking of the Anviloy inserts at sharp radii was noted.

The photographs of figure 10 show the TZM and Anviloy die inserts after 500 shots.

Figure 10

A second run was carried out some weeks later with all heaters operating 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 degradation by oxidation because the surface reached temperatures above 700°C (1292°F) where the oxide melts and volatilizes. This problem makes uncoated TZM a poor choice for die casting pure copper. Earlier work had shown TZM to be suitable for die casting a lower melting silicon brass alloy 7.

This work indicates that with sufficient preheat and maintenance of the operating temperature at 550°C (1022°F), Anviloy is a suitable die material for die casting of pure copper. High base material and machining costs are deterrents to its use, but Anviloy may offer a viable alternative in a part or parts of the die, such as the runner or gate, where the incoming metal temperature or flow rate are extreme.

Nickel-base Alloys

Three very different types of nickel-base alloys were evaluated with two inserts of each alloy in the test die. INCONEL alloy 617 is a 22%Cr, 12.5%Co alloy solid solution strengthened with 9%Mo. INCONEL alloy 718 is a gamma prime strengthened alloy containing 15.5%Cr 0.7%Al, 2.5%Ti and 0.95%Nb. INCONEL alloy 754 is a mechanically alloyed 20%Cr alloy with small additions of Al and Ti. A dispersion of Y2O3 is the principle strengthener giving resistance to recrystallization and excellent retention of high temperature strength. In a run of 250 shots, the inserts were preheated to 350°C (662°F) using the electrical resistance heaters and not permitted to fall below this temperature in the cooling portion of the cycle. Even though the 754 alloy has the highest strength at the copper melting temperature, these inserts began to show cracking in less that 50 shots. INCONEL alloy 718 began cracking in about 100 shots. Being a precipitation-hardening alloy, alloy 718 would be expected to have very low strength near the surface, which would reach the melting point of copper on each cycle but maintain its high tensile and yield values in the interior and back of the insert where ductility (17 percent -19 percent) is only fair. INCONEL alloy 617 showed only minor craze cracking after 250 shots at this low operating temperature (275°C /527°F below the minimum required). This test served to reveal alloy 617 as having the best combination of strength and ductility over the range of temperatures experienced by the insert. High fracture toughness in the service temperature range is apparently an important criterion for high temperature die materials.

A second extended run was done to evaluate the solid solution nickel-base alloys, INCONEL alloys 601, 617 and 625. Alloy 601 is a lower strength Ni-23%Cr alloy with 1.35%Al. It has only 14 percent elongation at 1177°C (2150°F) and a yield strength of only 15 MPa (2.2 ksi). Alloy 625 has 21.5%Cr, 9%Mo and 3.65%Nb and has somewhat higher tensile and yield strengths at room and intermediate temperatures, but is not quite as strong at 1100°C (2012°F) as alloy 617. Ductilities of both alloys 617 and 625 are quite high (45 percent minimum over the range of temperature) but slightly higher in alloy 617. At the point in time of these runs, the array of heaters and insert insulation shown in figure 11 had been developed to the point that the preheat and operating temperatures could be maintained at 540°C (1004°F) and with further tweaking for the next run, to the 625°C - 640°C (1157°F - 1187°F) range. In the course of an extended run with this die heating equipment, it became apparent that the amount of heat checking was markedly reduced as the operating temperature was increased. Finally in the last 330 shots at the highest operating temperature, there appeared to be no further deterioration of the die set. A total of 950 shots at the several progressively increasing operating temperatures had been made in this rather severe test. Clear distinctions between the three INCONEL alloys were difficult to discern. Alloy 601 may have somewhat inadequate tensile and rupture strengths for very long campaigns at or near 650°C (1202°F).

Figure 11

Chemical analysis of several copper test castings showed average iron pick up of 65 ppm, 5 ppm Ni and 0.074 wt% oxygen. The microstructures were very similar to that of figure 9 and were quite sound. The electrical conductivity was higher than that of the castings from the H13 die set averaging 99.9 percent IACS. Elimination of the steel shot sleeve in favor of a nickel-base alloy sleeve would presumably further reduce the iron and increase conductivity slightly.

Conclusions From Die Material Tests

Extended production runs will be required to prove the point, but these tests show promise that the INCONEL alloys 617 and 625 operated in the 600°C - 650°C (1112°F - 1202°F) temperature range are very promising die materials for die casting of copper motor rotors.

Although not tested in this study, Haynes alloy 230 is also a strong candidate die material. This alloy has slightly higher yield strength and ductility than alloy 617 and is weld repairable. Alloy 230 will be used in the first copper rotor production die set being built at this writing. An important conclusion from this work is that it is absolutely essential to operate at elevated temperature to extend die life. The higher die temperature reduces the surface-to-interior ΔT on each shot, which in turn greatly minimizes the cyclic expansion and contraction and thus the thermal fatigue mechanism causing heat checking and more severe cracking. Temperatures above 650°C (1202°F) are not required, and in fact would reduce productivity by increasing cooling time. A practical die heating and insulation design has been developed. A schematic illustration of the die inserts for rotor production equipped with resistance heaters and backed with insulation contemplated for production set ups is shown in figure 12. This design is undergoing further refinement and improvement with commercial installations currently underway.

Figure 12

Rotor Die Casting Trials and Performance Tests

A number of major motor manufacturers joined the program to cast copper rotors and test them in their facilities against a counterpart aluminum rotor. As of this writing, four manufacturers have reported data comparing performance of motors equipped with copper rotors and the standard aluminum rotor. These manufacturers supplied the rotor lamination stacks and underwrote the cost of motor testing on their laboratory dynamonmeters according to IEEE Standard 112B or in one case, to IEC 34-2.

For rotor casting, a three-platen master mold assembly was fitted to the Buhler horizontal die casting machine. In this conventional equipment for rotor die casting, the end ring inserts are located in the stationary and moving platens. The iron lamination stack is mounted and compressed on a steel mandrel and placed in a split cylinder insert in the center platen. The upper portion of this center platen is moveable to insert and remove the rotor stack and mandrel. For these trials, ordinary tool steel dies were used because only a few rotors were needed for testing. To maintain superheat, the heated shot sleeve surrounded by a thermal wrap was used for these trials. Rotors were cast according to a schedule of the machine real time shot control variables described above and half of the rotors were water quenched; the other half were air cooled.

Motor Performance Tests

Results of the motor tests have been described in detail elsewhere[8] and are only summarized here. The first copper rotors cast were for a 15 Hp motor and were 5.7 inches in diameter with a 6-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. Seven of the cast copper rotors from this group were tested. These had been cast over a range of machine parameters described above but 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 group of motors. 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 also that there 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 1 min compared to a 20-min air cool. This would be important to manufacturing efficiency.

The second rotor cast was larger for a 25 Hp motor. The end rings were 6.5 inches in diameter with a stack height of 9.5 inches. The squirrel cage contained 25 lbs of copper and required melting 39 lbs of copper per shot. The motor manufacturer provided sufficient laminations for 14 rotors. Motor tests of this second set of larger rotors showed even more dramatic results. This, in part, is due to the use of a rotor lamination slot specifically designed for copper.

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 temperatures. On completion of tests, the temperature of the stator winding of the motor with the copper rotor was 32°C (90°F) cooler than the aluminum design; the copper rotor was 29°C (84°F) cooler than the aluminum rotor. Lower running temperatures mean that smaller internal cooling fans can be used and this had a significant effect in reducing the parasitic component of the friction and windage losses on this motor designed for the copper rotor. Motor temperature translates directly to motor life and maintenance costs. As a general rule, insulation life is doubled 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.

The final set of rotors cast for another motor company were for a 4 Hp motor. The end ring was 3.54 inches in diameter, stack height 6.1 inches and contained 7 lbs of copper. Overall motor losses were reduced by 21 percent with the copper rotor compared to the aluminum.

Structure and Chemistry of Die-Cast Rotor Copper

Metallurgical examination of cast copper rotors confirmed that there was no welding of the copper conductor bars and the iron laminations and no copper penetration between 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 microshrinkage 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.%) 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 only slightly 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. The uniformity of conduction paths in these copper rotors shows up as a reduction in stray load losses and had not been expected. 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 cross-section of a copper rotor for a three-phase 4 Hp motor cast for another manufacturer is shown in figure 13. This 6-inch diameter rotor with 44 slots filled well with no visible porosity in the conductor bars. Tests of this copper rotor again showed a 38 percent reduction in rotor I2R losses, but the overall loss reduction showed no advantage over the aluminum rotor tested in parallel. This was due to the use of rotor laminations designed for the aluminum squirrel cage and operating near saturation in that motor. No advantage was possible from higher rotor currents when copper was substituted for aluminum.

Figure 13

A surprising conclusion from the study of machine casting variables was the remarkable insensitivity of the process to ram velocity 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, we conclude 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.

Conclusions from Motor Tests

Predictions of the benefits of copper in the rotor have been verified by these sets of rotors cast for and tested by four motor manufacturers. Overall motor efficiency was increased by a solid 1.2 to 1.6 percentage points. This is very significant in the light of 20 years of motor efficiency improvements using all of the readily available approaches. Copper rotors represent the only way to further reduce losses significantly without turning to expensive amorphous iron or to superconductivity.

The remaining barrier to acceptance of copper for the rotor is the economics of production by die casting, which is in turn primarily determined by die life addressed in Phase I of this project.

SSM Processing of Copper Casting Alloys

Aluminum alloy parts production has seen a revolution with the introduction of die casting semi-solid metal (SSM) billet. This process has allowed economic production of complicated parts with high density and better mechanical properties than obtained by conventional die casting or other methods. Copper alloy parts could benefit if the SSM process combined with die casting were available for these materials. For example, faucet components and brass lock hardware currently die cast in a zinc alloy and brass plated suffer from high reject rates due to porosity uncovered during polishing prior to the plating step. These would be strong candidates for manufacture via SSM.

In the past year, work to adopt SSM processing to copper alloys was undertaken at V Forge, Inc., Denver, CO, with Dr. Kenneth Young, a pioneer in SSM technology.

As with pure copper, die life is an issue for copper alloys. Melting ranges are somewhat lower, but are still considerably higher than those of aluminum alloys. The heated nickel-base alloy die technology developed for the copper rotor will be applied here. SSM processing in itself will also be an important factor in extending die life. Semi-solid metals are processed during billet production to produce a microstructure that will allow reheating for die casting to a temperature between the liquidus and solidus so that the billet is about half solid and half liquid but maintains its shape. As the semi-solid metal is forced into the die, there is essentially no superheat and only about half the heat of fusion thereby minimizing heat input to the die.

Figure 14

Work is in the early stages. Three copper alloys have been processed to the desired SSM structure and die cast using an available die set to produce the parts shown in the photograph of figure 14. A yellow brass similar to the forging alloy C37700, an aluminum bronze and a red brass alloy have been successfully processed. Research to develop a range of modified copper alloys for SSM processing having an attractive combination of mechanical and corrosion properties is underway. Commercial success will depend on devising a cost-effective approach to producing billet with the microstructural characteristics required for SSM processing, but not burdened with the premium price characteristic of aluminum alloy SSM billet. An approach being explored here is to produce slurry at the press by transferring molten copper alloy to a furnace equipped with magneto-hydrodynamic stirring where the semi-solid structure is generated on controlled cooling below the liquidus temperature. This SSM billet would then be transferred directly to the shot sleeve of the die casting machine.

The slurry at the press concept was tested using aluminum alloy 357, an alloy commonly used to make parts by the SSM process. So-called "virtual slugs" 2.5 inches in diameter and 5 inches long have been successfully re-heated and formed into parts. A group of copper alloy C90500 virtual slugs has been prepared at this stage awaiting a second series of forming tests. Alloy 905 is a copper-tin alloy, which offers a wide freezing range and is ideal for process development efforts. Slurry-making evaluations using essentially the same magneto-hydrodynamic approach used with aluminum alloy has been very encouraging.

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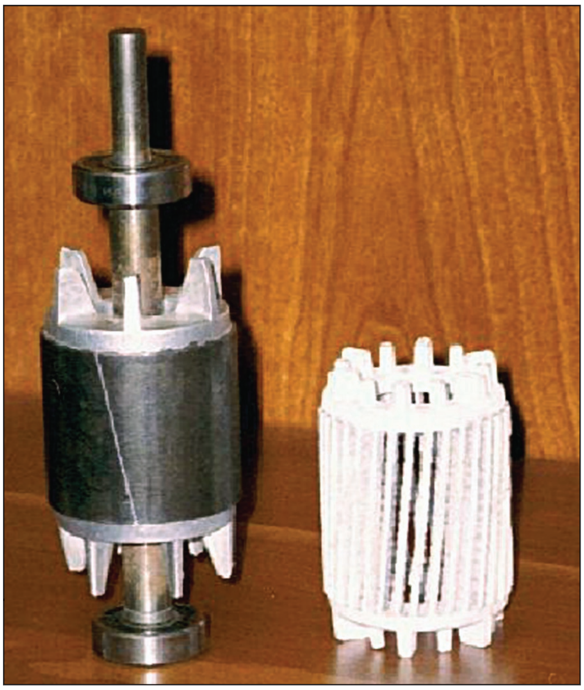


Fig. 1 – *Typical aluminum rotor and squirrel cage structure after dissolution of the iron laminations.*

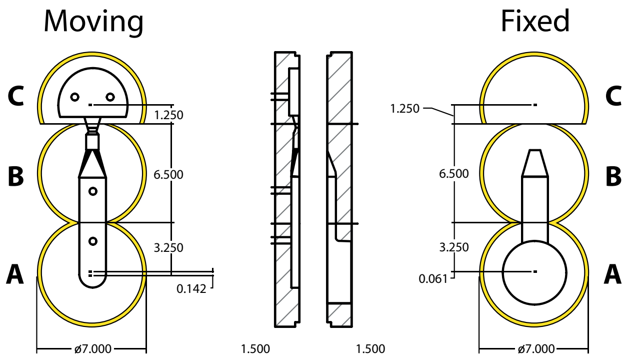


Fig. 2 – *Die material test die made up of six machined inserts.*

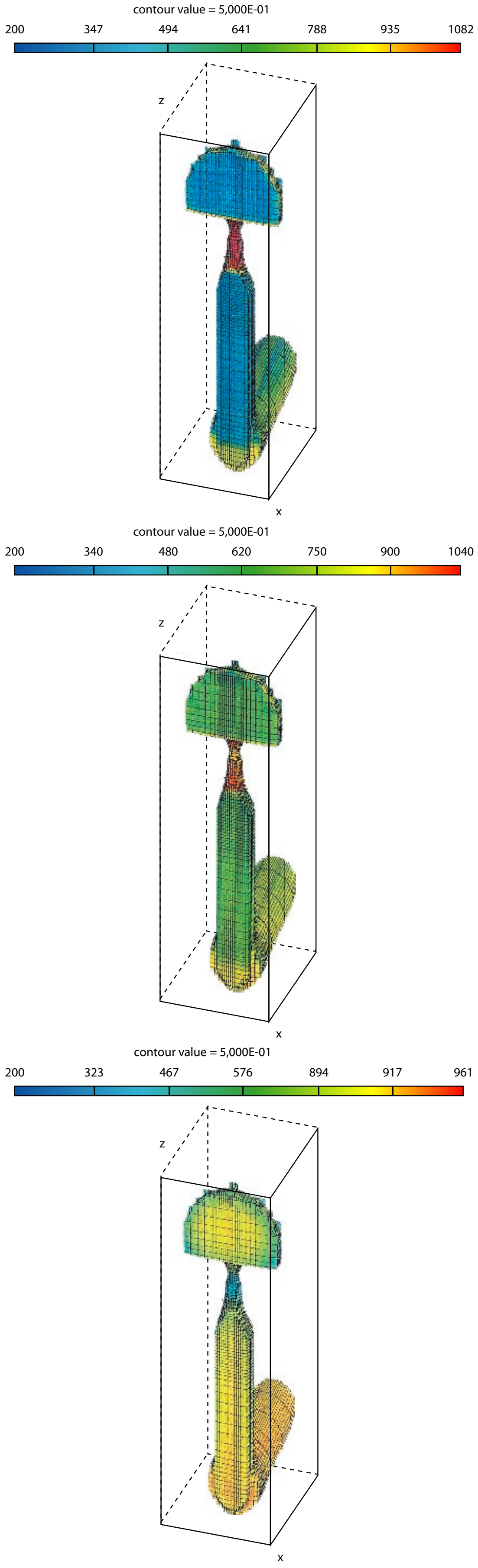


Fig. 3 – *Output of thermal modeling showing H13 die surface "painted" onto the test casting. A) At instant of fill with 1200°C (2192°F) copper. B) 0.5 sec. after fill. C) 6.5sec. after fill.*

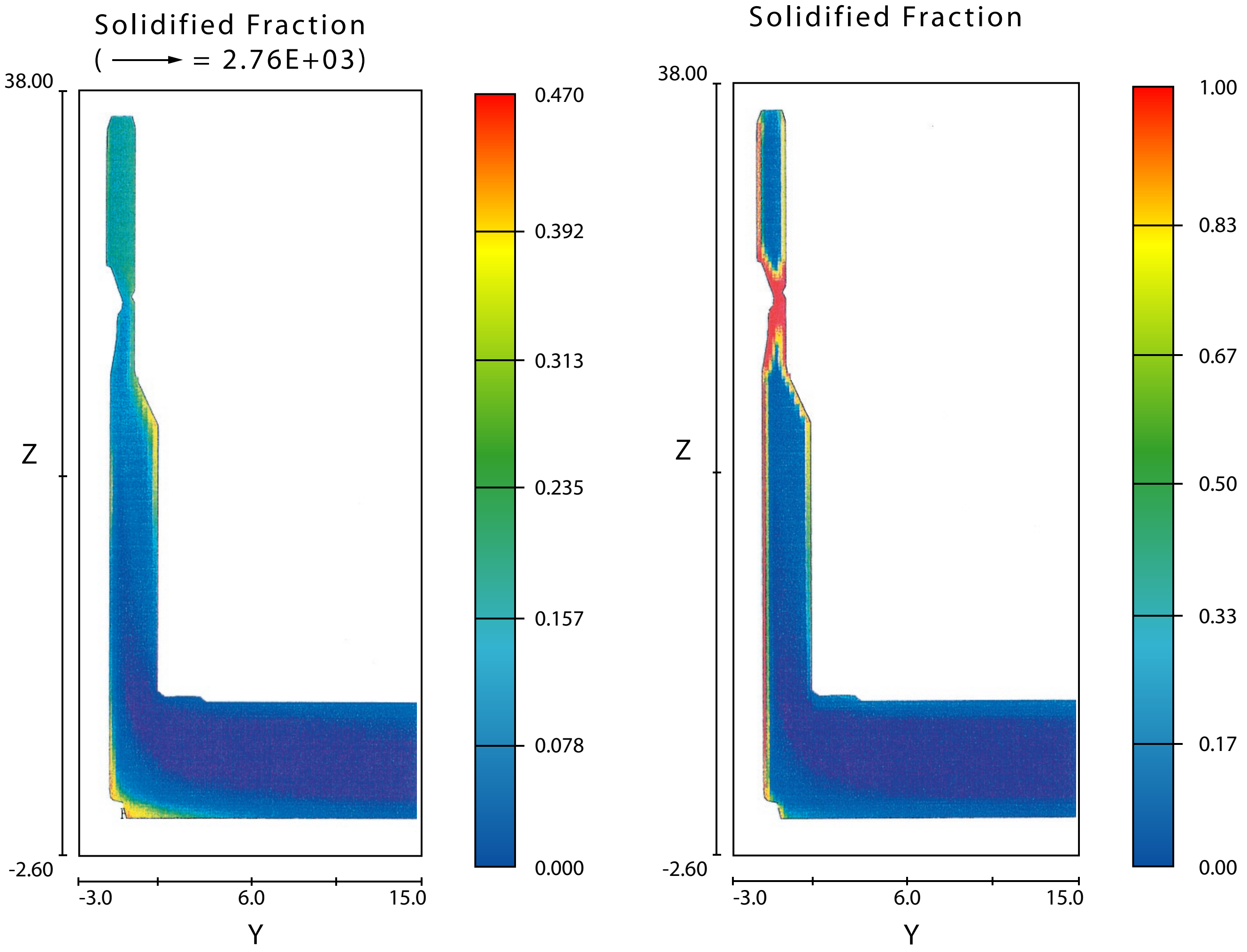


Fig. 4 – *Solidified fraction of copper in H13 die at instant of fill. B. 0.53 sec. after fill.*

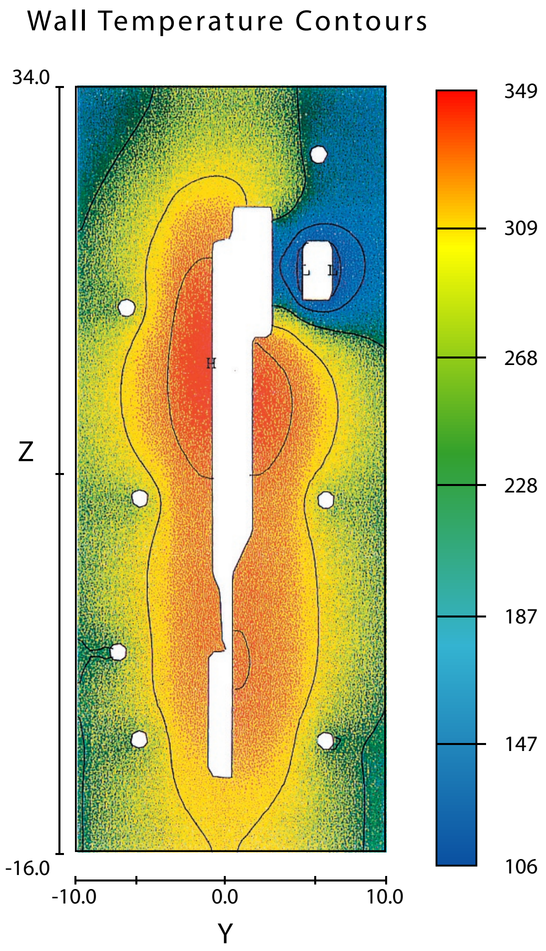
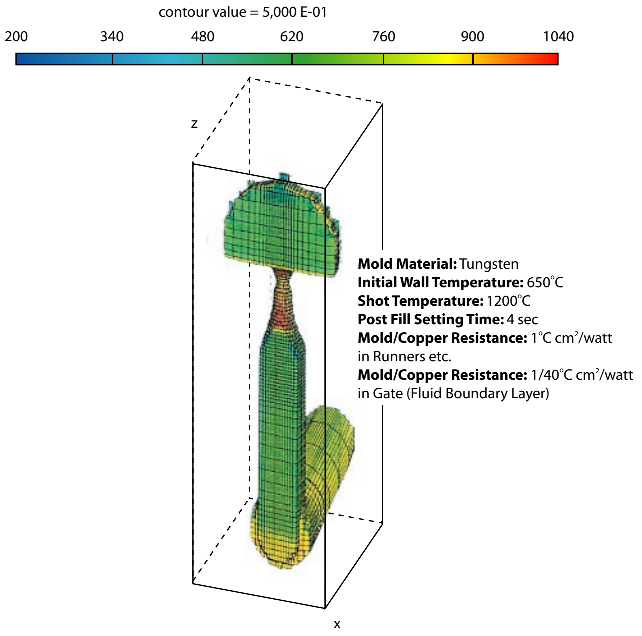


Fig. 5 – *Die temperature contours for H13 dies after five cycles. Cooling channels are indicated.*



Mold Material: Tungsten
Initial Wall Temperature: 650°C
Shot Temperature: 1200°C
Post Fill Setting Time: 4 sec
Mold/Copper Resistance: 1°C cm²/watt in Runners etc.
Mold/Copper Resistance: 1/40°C cm²/watt in Gate (Fluid Boundary Layer)

Fig. 6 – *Tungsten die surface temperature distribution as "painted" on to the cast object. Initial wall temperature, 650°C(1202°F), copper melt temperature, 1200°C (2192°F), die/copper resistance at runner, etc., 1°C cm²/watt. die/copper resistance at gate, 0.25 °C cm²/watt.*

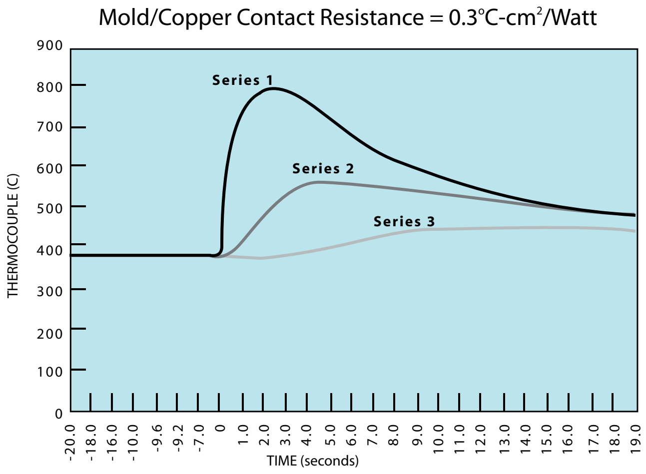


Fig. 7 – *Predicted die temperature-time profile for tungsten. die/copper contact resistance, 0.3°C cm²/watt.*

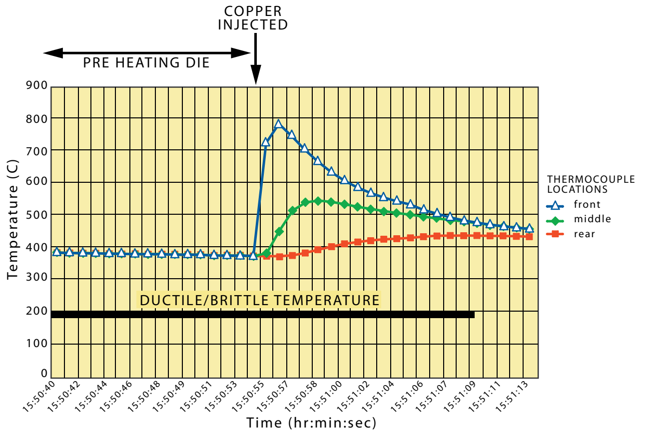


Fig. 8 – *Measured die temperature-time profile for tungsten preheated to 380°C (716°F).*

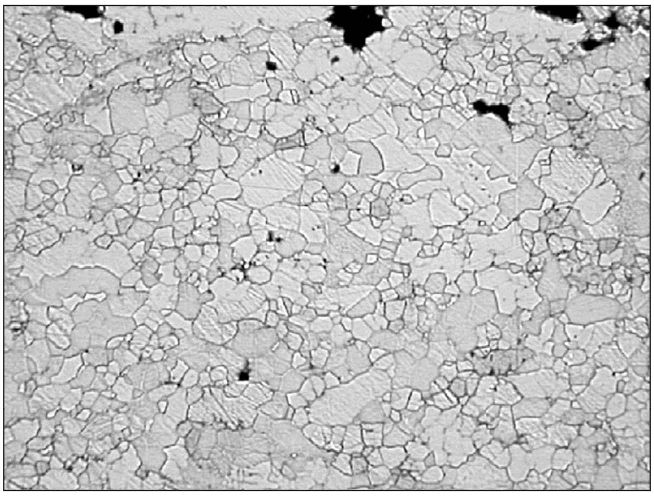


Fig. 9 – *Microstructure of die cast copper specimen at gate region. 50X.*

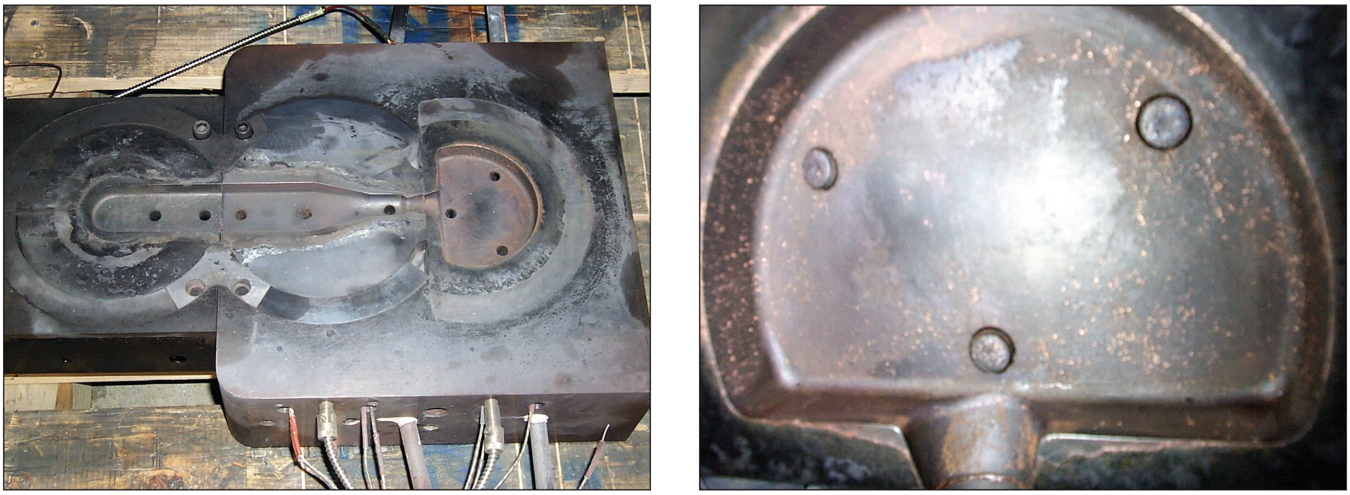


Fig. 10 – *Left–Moving half of TZM and Anviloy die inserts after 940 shots. TZM is in the bottom (left) position and Anviloy in the middle and upper positions. Right–Close up of Anviloy die insert after 500 shots.*

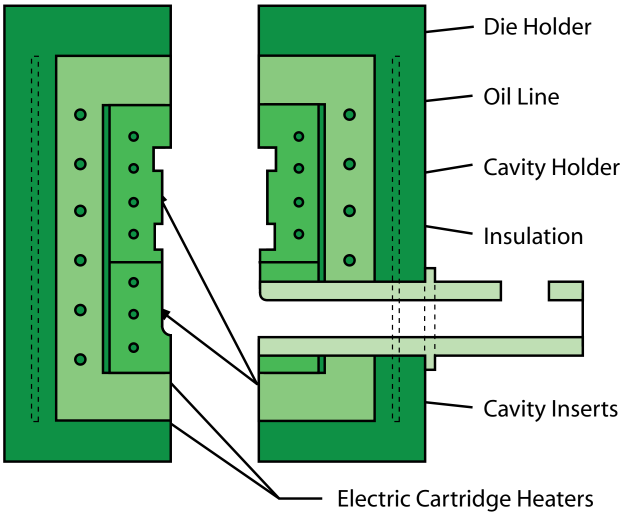


Fig. 11 – *Schematic illustration of placement of electric resistance heaters and insulation in the die material test set-up developed in the course of this study.*

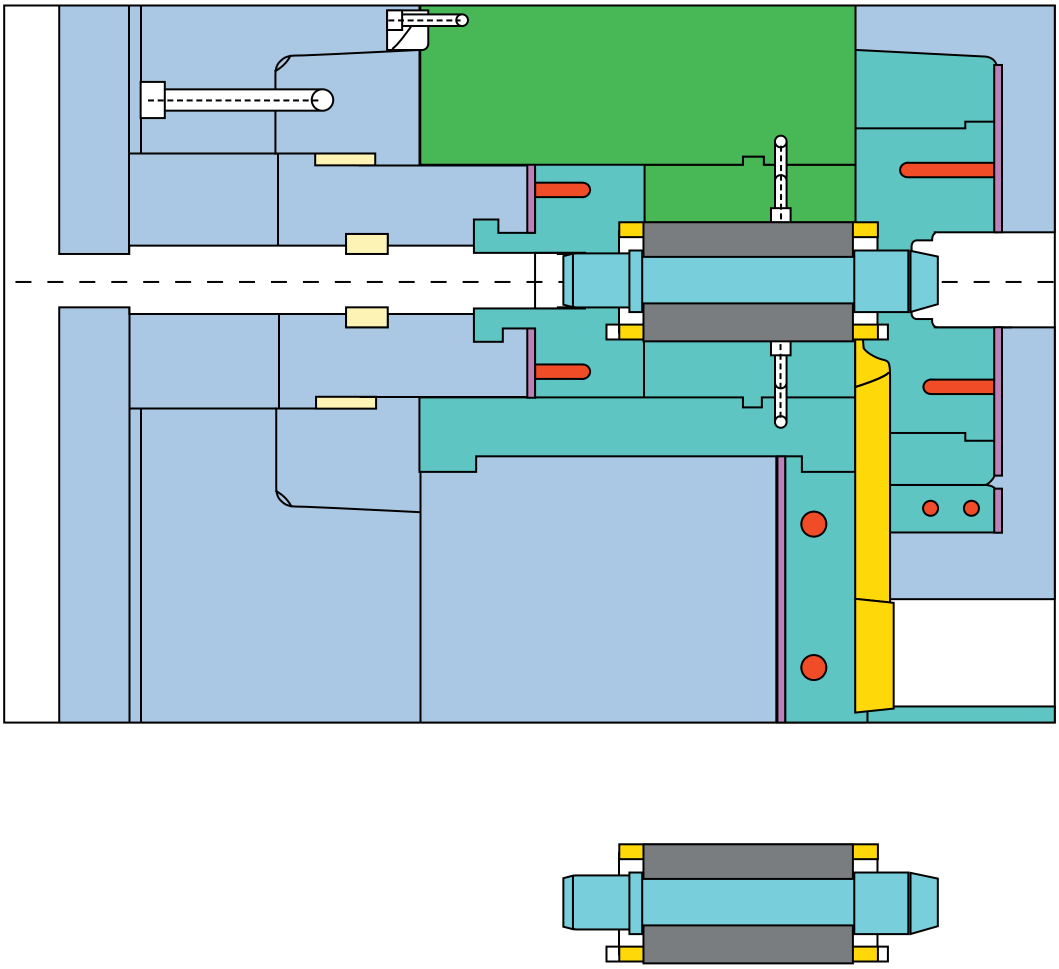


Fig. 12 – *Horizontal pressure die caster with tooling for rotor casting in closed position.The arbor (dark blue) and the steel rotor laminations (dark gray are shown in the insert and in position in the machine. Copper from the shot sleeve biscuit, runner bar and end rings is shown in yellow. The nickel alloy and 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 plate of the master mold set are shown in light gray. (Courtesy of DieTec,GmbH).*

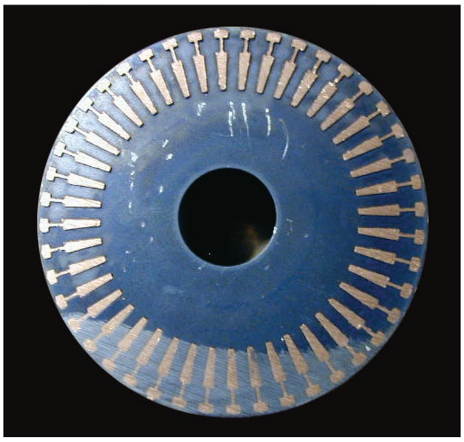


Fig. 13 – *Cross-section of rotor for 3-phase motor showing copper filling the conductor bar shots.*

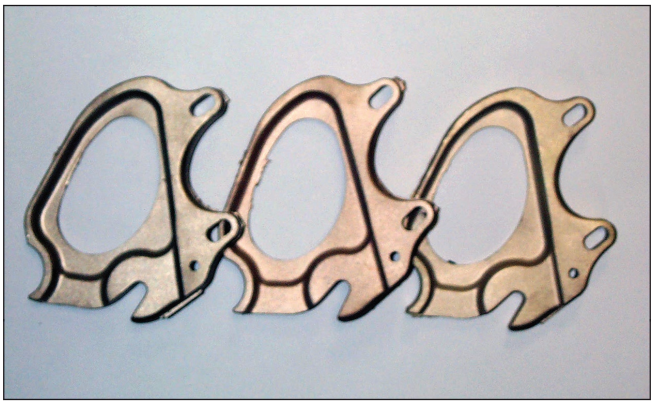


Fig. 14 – *A part produced in three copper alloys by die casting SSM-processed billet.*