Technology Transfer Report - The Die-Cast Copper Motor Rotor

**by the
Copper Development Association Inc.
and the
International Copper Association, Ltd.**

**260 Madison Avenue
New York, NY 10016
USA**

212-251-7200

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FOREWARD

It is our pleasure to introduce this report to you, the motor manufacturer. We trust that this document will facilitate incorporation of the copper motor rotor pressure die casting technology into your motor designs and manufacturing processes. Our thanks go to the contributing specialists in die-casting technology, die-design, motor design and testing and to the various project sponsors and to the participants in the development and prototype phases who believed in and supported our vision.

The technology transfer report is a "living document" and will be continuously updated and refined. On November 30, 2000, the Copper Development Association Inc. (CDA) filed a U.S. patent application, "Apparatus and Method for Die Casting." CDA will grant free licenses for the asking of the technology to all interested parties for the sole purpose of die casting copper and copper alloys.

Introducing copper into the rotor should allow your company to cost effectively reach the next frontier in motor development. The higher conductivity of copper enables you to envision a range of design options, including but probably not limited to:

1. Reaching the next higher level of energy efficiency, possibly with the same motor size: For example when moving from the European Union voluntary standard efficiency level 2 to the higher efficiency level 1, or when upgrading from the EPAct (Energy Policy Act of 1992 of the United States) mandated efficiency level for general purpose multi-phase induction motors to the voluntary higher efficiency defined and labeled as NEMA Premium (National Electrical Manufacturers Association).

2. Maximizing energy efficiency to higher and even "super-premium" levels by redesigning both rotor with copper conductors and stator by increasing volume of copper winding wire.

3. Maintaining a specific energy efficiency level while reducing motor size and possibly weight.

4. Reducing total manufacturing cost at the same efficiency level.

We believe that the end-users of motor driven systems, your direct and indirect customers, will welcome these possibilities for new or improved products. Benefits to the end-user when they introduce high efficiency motors into their long running processes and in heavy-duty cycle equipment are many:

1. Economic benefit of reduced electrical energy consumption year after year due to significantly lower losses, with attractive payback and return on capital investment.

2. Economic benefit of motor life, with proper maintenance, being potentially extended by several years due to cooler operation with fewer repairs and re-windings.

3. Image enhancement as end-use companies can credibly project labels such as "green", "responsible corporation", "environmentally friendly" because they have consciously reduced energy consumption or improved energy efficiency within their processes contributing to reductions in greenhouse gas emissions and to the sustainable development of the countries and societies in which they operate.

The decision is yours. We are available to provide technical assistance with the technology transfer to your production facilities and recommendations for investments in the necessary equipment and components. We also recognize that some mechanical properties and motor performance data may change when replacing aluminum with copper. This may require minor design changes and adjustments. While this is mainly your company's area of expertise, our experts would be glad to discuss these aspects.

In addition, in partnership with other organizations and government agencies, generic promotion and awareness campaigns aimed at the key decision-making personnel in the electric motor using industries including senior management are or will be supporting your company's own sales and marketing efforts.

Finally, we would like to offer a suggestion to those companies that customarily test and report motor performance using IEC 34-2 method. In order to fully appreciate the potential in the reduction of energy losses made possible by the introduction of copper conductor into the rotor, we recommend additional evaluations with the IEEE method 112-B or Canadian Standard C-390 or similar standards that assess stray load loss. Indeed, test data have shown that not only are the losses in the rotor conductor bars reduced with die-cast copper as would be expected, but also other energy loss components, including stray load, have also been substantially reduced. Introducing a predetermined value for stray load loss as is the case with test method IEC 34-2 may lead to an underestimate of the energy efficiency gains of the newly designed motor with the copper rotor.

INTRODUCTION

In 1997, the Copper Development Association, Inc. (CDA) undertook a project to substitute copper for aluminum in the "squirrel cage" structure of the motor rotor as a means to improve the electrical energy efficiency of the induction motor. After many years of improvements to motor efficiency, few technical avenues remained for significant efficiency improvements. The copper rotor appeared to be the best approach and much more cost effective than introducing amorphous iron laminations or superconducting windings. Motor modeling by a number of manufacturers had shown that motors with copper-containing rotors would yield overall loss reductions from 15 to 20% compared to the aluminum standard. In the U.S. alone, a one percent increase in motor efficiency would save 20 billion kW hours per year or 1.4 billion US dollars in electricity (at 7 cents per kW hour).

Pressure die-casting has been the standard industry method for production of the aluminum rotor. Acceptance of the copper rotor by motor manufacturers demanded that the copper counterpart be producible by the same equipment. Therefore, CDA first addressed the main technical barrier to the pressure die casting of the relatively high melting point metal, copper; i.e. sought to solve the problem of inadequate die life. To attack this problem, CDA assembled a consortium including several major motor manufacturers. This project was funded largely by the world copper industry through the International Copper Association with participation by the United States Department of Energy and the Air Conditioning and Refrigeration Technical Institute. Formcast Development, Inc.* in Denver, Colorado, provided die casting expertise and a Bühler 660 Tonne (750-ton) horizontal real time, computer shot controlled die casting machine for the trials. DieTec, GmbH of Gassau, Switzerland, designed rotor die casting tooling and established parameters for operation of the Bühler machine in the copper rotor casting trials.

Prior to copper die casting experiments, a computer analysis of heat transfer in the dies was performed. This showed clearly the steep thermal gradients from the die surface when casting a high melting point metal and the effects of material thermal conductivity and die temperature on these gradients. Because of the significance of this modeling exercise to understanding die behavior, it is presented in the next section. Phase I of the CDA project successfully identified suitable high temperature mold materials and demonstrated that operating the dies and shot sleeve at elevated temperatures could substantially extend tooling life [1, 2]. A shot-by-shot induction melting method was developed to conveniently and safely provide molten copper for the die casting machine. Valuable experience in die casting copper rotors was gained in Phase II of the project. Motor manufacturers subsequently evaluated several of these copper rotors for electrical performance in motor tests [3, 4]. These results are summarized here.

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* Formcast Development, Inc. was dissolved in early 2004; die casting of copper rotors for manufacturer evaluation is now done at Vforge, Inc., Englewood, CO.

COMPUTER ANALYSIS OF HEAT TRANSFER IN DIE CASTING MOLDS

Experimental work on mold materials for die casting copper and copper rotors had been preceded by a program of 3-D computer analysis of heat transfer in the mold material test dies to model and optimize the thermal design. Flow Simulation Services, Inc. of Albuquerque, New Mexico did this work under contract to ThermoTrex Corporation (now Trex Enterprises). ThermoTrex had been an industrial partner at the initiation of the project based on their expertise in high-speed chemical vapor deposition. At the time, this technology was a promising approach to producing net-shape tungsten dies. ThermoTrex with CDA had been the recipient of a U.S. Department of Energy NICE[3] grant to pursue this technology. Computer analysis of the heat flow and thermal gradients in the dies was a valuable tool in understanding the thermal fatigue failure mechanism and how to avoid it.

Temperature profiles in H-13 (tool steel) were generated for this material in the test die devised for die material evaluation tests. This compound die made up of three die inserts on both the fixed and moving sides is shown in the drawings of Figure 1.

Die surface temperature distributions at the instant of filling with 1200°C 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 cm² /watt, a value in the middle of the range found in the die casting literature. Figure 2A shows the result from this model for the mold surface temperature distribution immediately after filling of the mold. In this figure, to avoid representational problems, the mold surface temperature has been "painted" onto the surface of the cast object. In this case the casting surface will actually be hotter than the mold surface because of the surface heat conducting resistance. In fact, in this example, the investigators assumed that
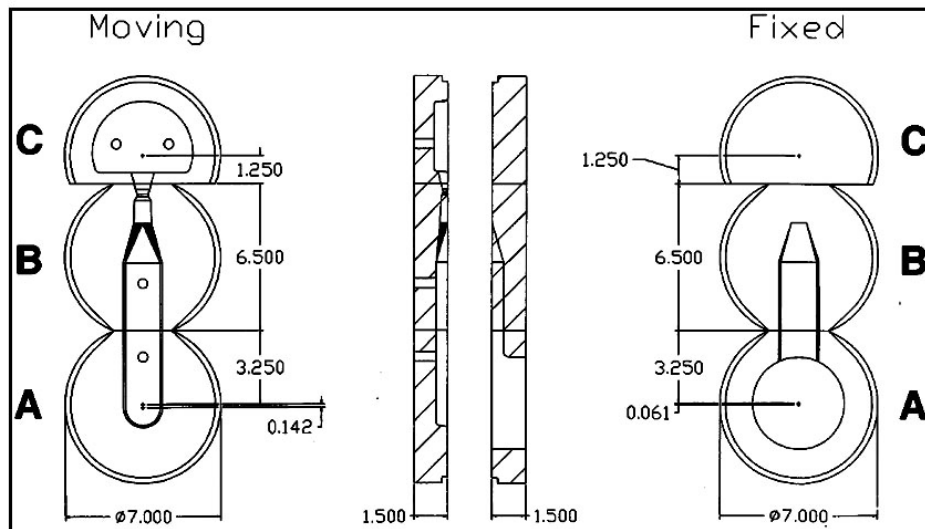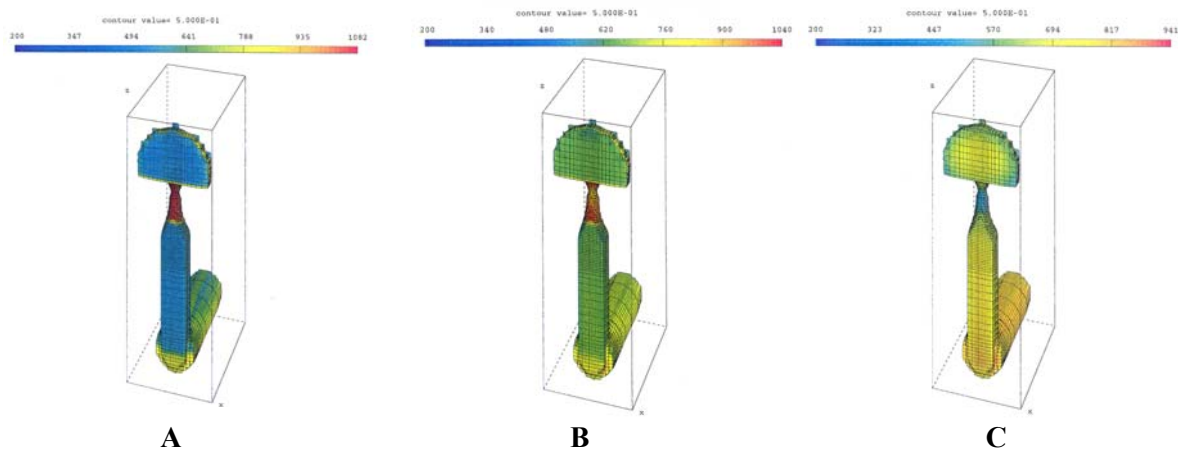

**Figure 1 - Mold material test die made up of six machined inserts.**

Figure 2 - H-13 (tool steel) mold surface temperature "painted" onto cast object.. Coating contact resistance of 1 °C cm² /watt. No coating at the gate. A - at the instant of mold filling with 1200°C copper. B – 0.5 sec. after fill. C – 6.5 sec. after fill.

that coating the narrow gate region would be difficult and assigned a very low heat flow resistance to this region. Thus the mold 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, by 880°C. Because of the low thermal conductivity of H-13 tool steel, the body of the mold is still at 200°C. This implies that the surface has a temperature-induced strain of at least 1.19%, an enormous strain to sustain on a cyclic basis.

Immediately after filling, the coated areas of the mold are only in the range of 550-600°C, or 350°C above the initial temperature and the bulk of the insert. The mold surface at the biscuit area at the end of the ram in the shot sleeve is at about 800-850°C.

At 0.5 seconds after casting (Figure 2B), the temperature in the uncoated gate area has started to drop, but the rest of the mold surface is getting hotter. 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 range. After 6.5 seconds (Figure 2C), the gate area is relatively cold but coated areas of the larger volume sections of the casting have risen to 750 to 900°C.

Thus in the H-13 tool steel, we expect from these calculations that the mold surface temperature will rise to values ranging from 825°C to over 1000°C 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 °Ccm² /watt over these surfaces. These high surface temperatures imply that substantial surface strain occurs everywhere in the H-13 molds.
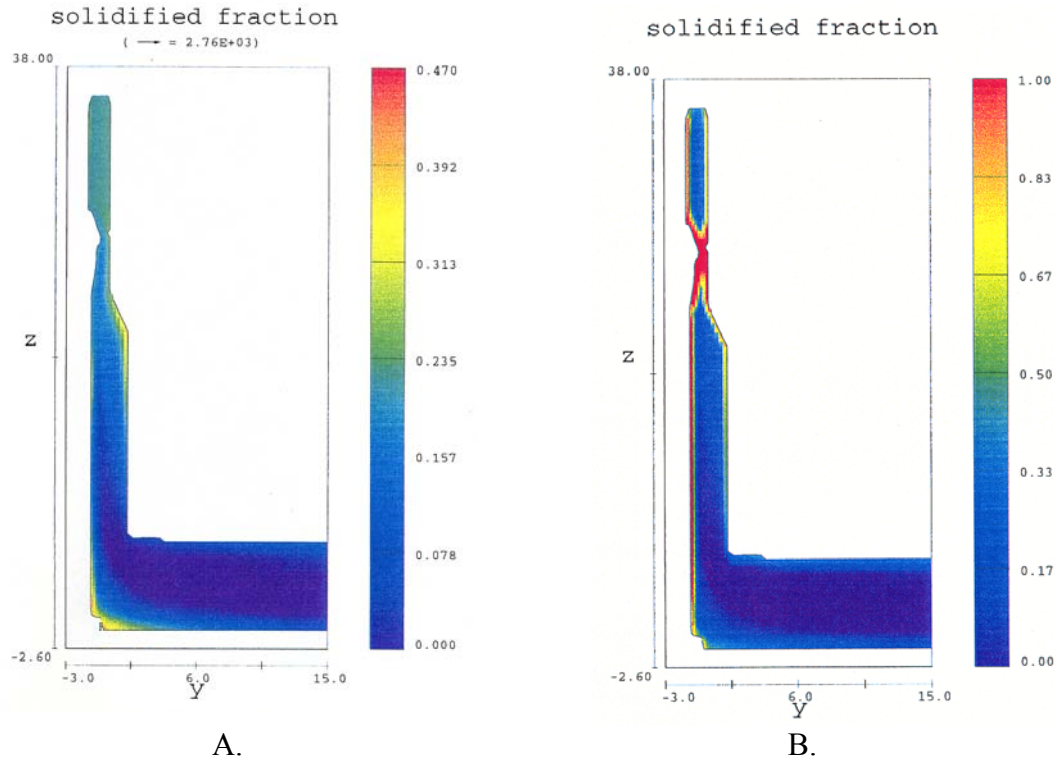
Figure 3 - Solidified fraction of cast copper in H-13 (tool steel) mold at instant of mold fill (A) and 0.53 sec. after mold fill (B).

Figure 3A 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 solids. 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% solid and 75% liquid, so the temperature is at the melting point of pure copper; i.e. 1083°C. 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 3B shows the solidified fraction 0.53 seconds after injection was complete. The gate region is already 100% solid as are some regions near several of the walls. Elsewhere the copper is at the melting point, only about 30% solid, with a large amount of residual heat of fusion to "give up" to the walls before it can cool below 1083°C. It is this large amount of residual heat that will continue to heat the mold surfaces to high temperatures after casting is over. This was shown at 6.5 seconds after casting in Figure 4.

This modeling method was used also to look at the effect of the oil and water-cooling in the mold holders of the Bühler 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 at the beginning of the shot of the H-13 die rises from the initial value of 200°C, established by oil heating, to about 360°C. This turns out to be affected very little by placement of the cooling lines. Figure 4 shows the die temperature contours for the H-13 test die after five cycles (just prior to the sixth shot).
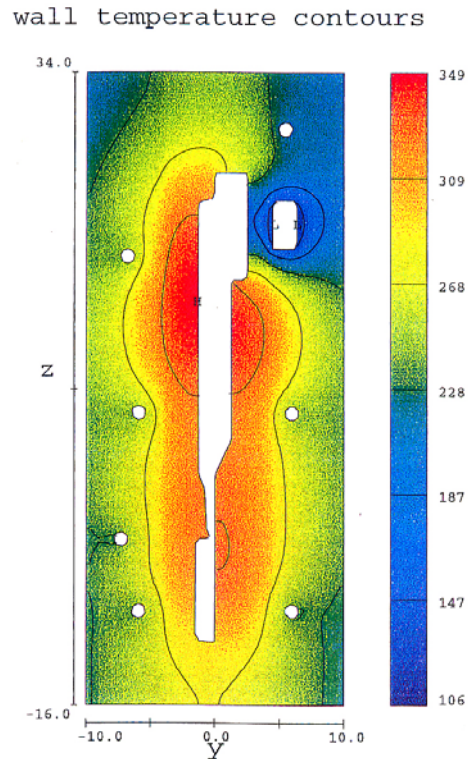
Figure 4 - Die temperature contours for H-13 (tool steel) dies after five cycles. Cooling channels are indicated.

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 holder blocks 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 5. 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 to 800°C, only a 150°C increase. The smaller increase compared to the H-13 example is in part due to the higher thermal conductivity of tungsten.
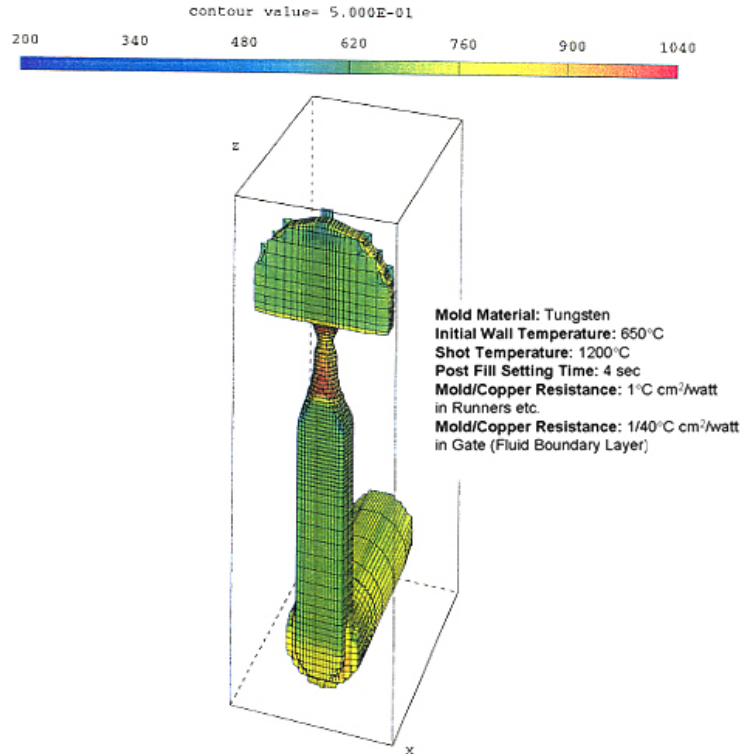
Figure 5 - Tungsten die surface temperature distribution as "painted" onto the cast object at instant of mold fill. The initial wall temperature was 650°C; copper melt temperature 1200°C; die/copper resistance at runners, etc. 1°C cm² /watt; die/copper resistance at gate 0.025 °C cm² /watt.

Temperature-time profiles in a tungsten insert preheated to 380°C are shown in Figures 6 and 7 for thermocouple locations near the front, center and rear of the insert. Model predictions using a die/copper contact resistance of 0.3 °C cm² /watt are shown in Figure 6. Figure 7 shows the actual measured temperatures during the shot. The agreement is excellent. A ΔT of about 400°C 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. The ductile/brittle transition temperature at about 200°C for tungsten is also indicated on Figure 7. This means that the machine operator cannot use the first few shots to achieve the operating temperature without cracking the die.

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.
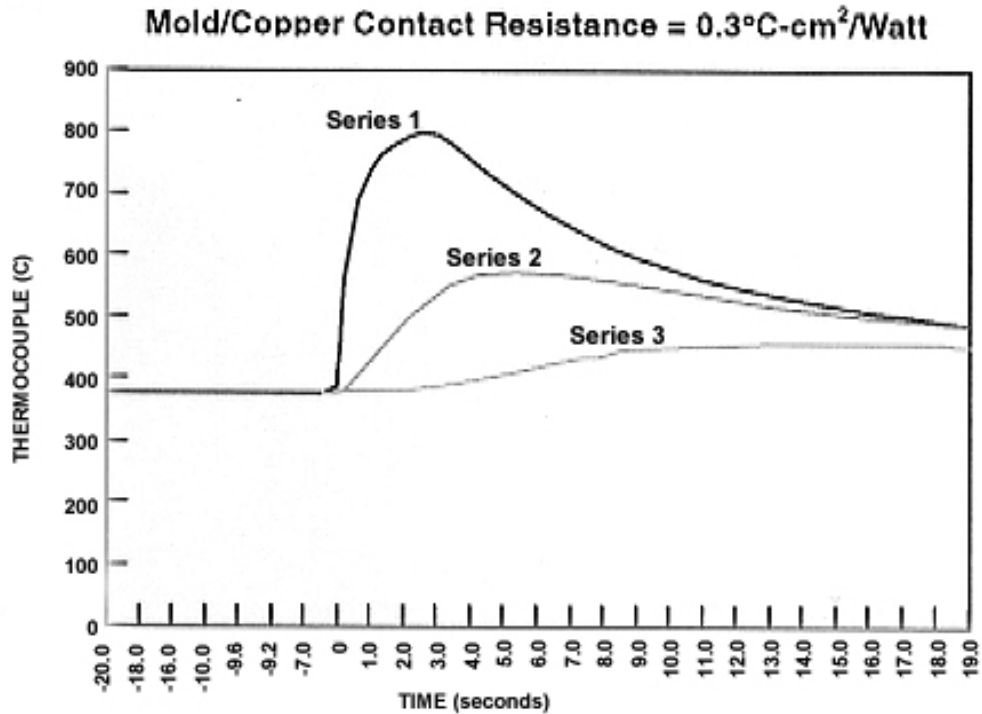
Figure 6 - Predicted die temperature – time profile for tungsten mold. Mold/copper contact resistance = 0.3 °C cm² /watt.
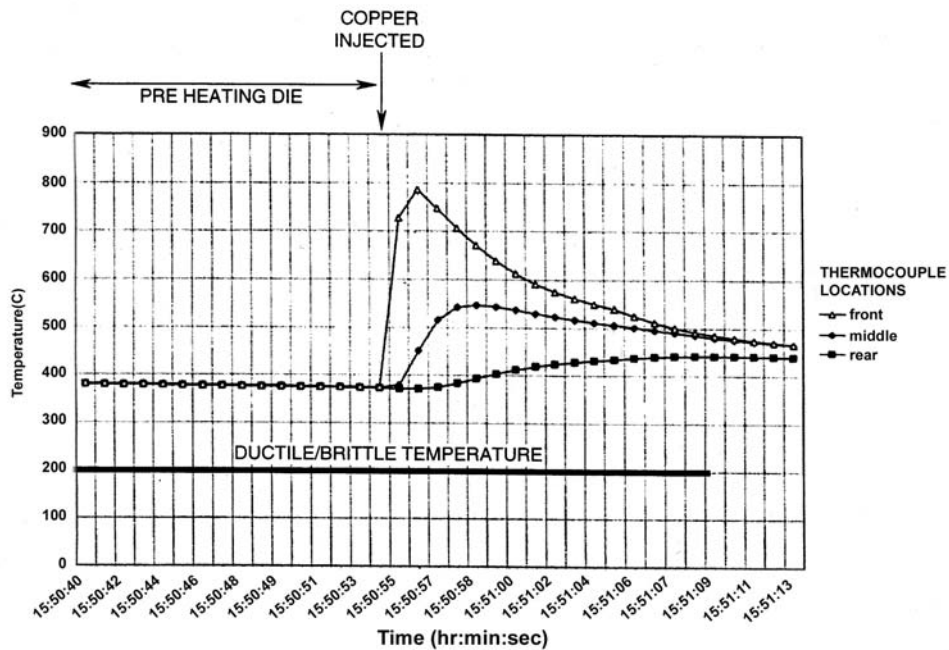
Figure 7 - Measured die temperature – time profile for tungsten mold preheated to 380°C.

HIGH PRESSURE DIE CASTING OF COPPER ROTORS

Casting Trials

Phase II of the project allowed the team to gather valuable experience in copper motor rotor casting. This project did not attempt production of large numbers of rotors but several hundred have been cast as part of the development effort and to provide copper rotors for evaluation by motor manufacturers. Following some initial shots to establish machine parameters to completely fill the rotor conductor bar volume and far end ring die, copper rotors were cast for four motor companies. Using the Bühler 660-mT (750-ton) horizontal pressure die caster at Formcast Development, Inc. Production of these test rotor castings served four main purposes:

- Established the range of machine parameters under which sound castings could be made.
- Served as a vehicle to design of die inserts and methods of insert heating and insulation.
- Allowed for physical examination of the cast copper for evaluation of chemistry, conductivity, microstructure and porosity, and correlation with machine operating conditions.
- Provided test rotors for motor company measurements of motor performance with a copper rotor, and correlation of performance with pressure die casting parameters.

Casting Variables Examined in the Trials

Although, as mentioned above, the CDA-Formcast team has not cast large numbers of copper rotors, casting and evaluation of rotors for four motor companies has been very instructive. Because only a small number of test rotors were to be cast for evaluation, available H-13 die inserts were used. At the time of the initial rotor-casting trials, the die inserts had not been equipped with electrical resistance heaters and insulation to achieve the optimum operating temperature for long die life. These practices were evolving in the course of the trials for four motor manufacturers. Instead, the dies and shot sleeve were preheated and heated between shots with an oxy-acetylene torch.

The real-time shot control capability of the Bühler 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. The machine features independent computer control of die closure and shot sleeve velocities and pressure providing accurate and replicable machine settings for each shot.

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 81 MPa (11,750 psi) to a lower value of about 35.5 MPa (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 that the conductor bars were cool enough to maintain the compression of the iron laminations. Adequate "dwell" times have been 14 to 22 seconds in the rotor casting trials to date.

Post-Casting Treatments

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 or coating 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 (Figure 8) 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.

Figure 8 - Water quenching of die cast copper rotors after extraction from dies. This operation reduces cooling time and although not necessary for performance, is an aid to productivity by shortening handling time. Operation could be mechanized for production.

Control of Porosity in Rotor Die Castings

Copper is a very fluid metal and, apart from its high melting temperature, is readily die cast. High pressure die casting is the most economical process to form the squirrel cage

of the induction motor rotor, but the high rate of introduction of liquid metal to the die cavity generally invariably results in some distributed porosity in the casting. Porosity in the end rings and conductor bars of die-cast aluminum rotors has long been a problem. Copper rotors cast in this program and tested by several motor manufacturers were remarkably easy to balance and showed significantly reduced stray load losses. Both factors seemed to indicate the absence of large pores in the structure. The low stray load losses are only possible when the currents in each rotor conductor bar are essentially equal. The existence of large pores would reduce the bar cross section and current in that bar. Copper rotor castings for a large motor produced after those described above were found to be difficult to balance. Sectioning of the end rings revealed large pores. This porosity was as much as 25% in some castings and 8 to 10% in others. Subsequent examination of rotors for a 15 Hp (11.2 kW) motor also revealed more porosity than expected (Figure 9). These findings prompted an investigation of the origins of the porosity and means to eliminate formation of large pores. The work is fully described elsewhere [5] and is summarized here.


Figure 9 – Photographs of sectioned end rings from a 15 Hp (11.2 kW) copper rotor typical of baseline die casting conditions.

Flow 3D software using computational fluid dynamics methods was used to simulate metal flow into the die cavity. The output for the model simulations was a series of flow videos. These were analyzed to identify shot speed – time profiles that would cause large pores in the end rings or conductor bars. Profiles to eliminate large pores in favor of uniformly dispersed fine pores were sought. The model of the rotor squirrel cage with the gates and runner bar is shown in Figure 10. Simulation of the baseline casting conditions was performed to determine if the observed void pattern could be predicted. This baseline shot profile extends the initial slow plunger speed so that about 10% of the gate end ring is filled before transition to fast shot speed to complete the fill.

The simulation is shown in Figure 11. This is a single frame from the Flow 3D video. These representations show only the skin of the casting next to the cavity wall and the skin surrounding any pores present. Pores are seen by the skin formation around the air bubble. Otherwise the casting appears to be empty where metal is actually present.

Arrows in Figure 11 show the predicted porosity in about the same locations as seen on the sawed cross sections of Figure 9. The video of the ejector end ring also showed bubbles consistent with the physical examination, but the videos also seemed to indicate bubble formation in the conductor bars which may or may not be
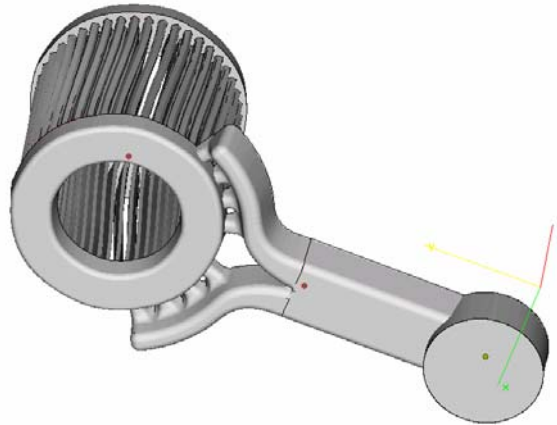
Figure 10 – Model of squirrel cage with gates and runner. Symmetry of the part allows simulation of the fill to be done on half of the model thereby saving computer run time.
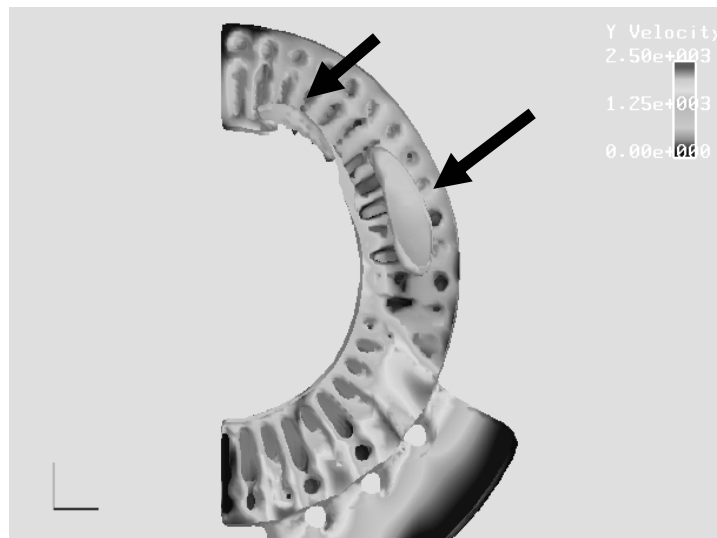
Figure 11 – Simulation of the gate end ring fill for the baseline shot profile used for production of copper rotors early in the program.

forced into the ejector end ring later in the fill. Large pores or bubbles were never seen in the conductor bars of rotors that had been machined to expose the point of largest bar thickness. As shown in Figure 12, only a few pin head size pores are seen in the bars.

The significant result from the model simulation of fill with several trial shot profiles was the discovery that slow pre-fill of the cavity beyond the gates of 40 to

Figure 12 – Photograph of copper rotor turned on the OD to expose the conductor bars. Trapped air bubbles are not seen in the bars but are clearly visible in the end ring.

as much as 55% was predicted to be a strategy for avoiding large pore formation in the end rings.

A number of copper rotors were cast to test the Flow 3D simulation predictions. Rotors 5.7 in. (145 mm) in diameter by 5.25 in. (133 mm) high were cast using the 660-Tonne real time shot controlled Buhler horizontal die casting machine at Formcast. This machine provided for precise programming of the shot profile. The die used for the trials was a commercial two-plate rotor die, edge gated, with a vertical core pull to assist with rotor stack insertion and ejection of the cast rotor. Copper in the form of chopped C10100 wire rod was induction melted under nitrogen cover on a shot-by-shot basis using a push-up crucible and the 60-kW power supply. The shot weight was 24 to 26.5 lbs (11 to 12 kg).

As concluded above, commercial production of copper rotors requires the heated nickel-base alloy dies. This type of tooling was not available for these experiments, so an H-13 steel die set was used. Die temperatures measured prior to each shot at six points on the die faces ranged from 240 to about 600°F (115 to 315°C). This is not nearly as hot as the 1200°F (650°C) die temperature prescribed and known to be

essential to extending die life. With relatively cold tool steel dies, a rather high melt temperature of nearly 2600°F (1425°C) was found to be necessary to compensate for heat loss from the liquid copper to the cooler shot sleeve, die inserts and lamination stack. The high melt temperature was critical to avoid freezing in the gates with the slow pre-fill programs being tested. The shot sleeve was heated to 840°F (450°C) to help in this regard.

The shot profile was varied so that the speed transition occurred below the gates about half way up the runner and at pre-fills of 33 and 55%. Results are show in the sawed cross sections of Figure 13. Porosity is seen to decrease markedly with increasing pre-fill compared to acceleration before the metal reaches the gate. Presumably the amount of pre-fill cannot be increased indefinitely. Additional experiments to determine the limit would be valuable.

EVALUATION OF CAST COPPER ROTORS

A total of about 140 rotors were cast for four motor manufacturers to evaluate in their own laboratories. A number of these rotors were physically examined to assess structural integrity and analyzed chemically to determine the extent of pick up of impurities in die casting.

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. Microstructures of the cast copper are shown in Figures 14 and 15. The conductor bars showed small defects at the copper-iron interface and lamellar 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.% 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 and 98.7% 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 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% voids in the first shots and 8 to 10 % in the rotors tested for electrical performance. Die casting machine operating parameters to minimize the occurrence of large pores was discussed above. 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.

Speed transition in the runner


33% pre-fill
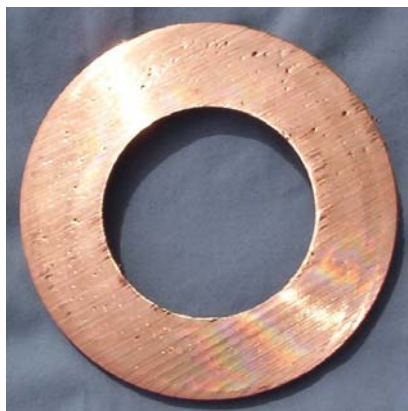
55% pre-fill

Figure 13 – Photographs of sectioned end rings with increasing pre-fill. Ejector end rings on left; gate end rings on right.

Figure 14 - Macrostructure of cast copper showing dendritic grain structure at the steel chill interface and a largely coarse equiaxed structure in the center. Very small volume fractions of oxide and porosity are seen. 50X.
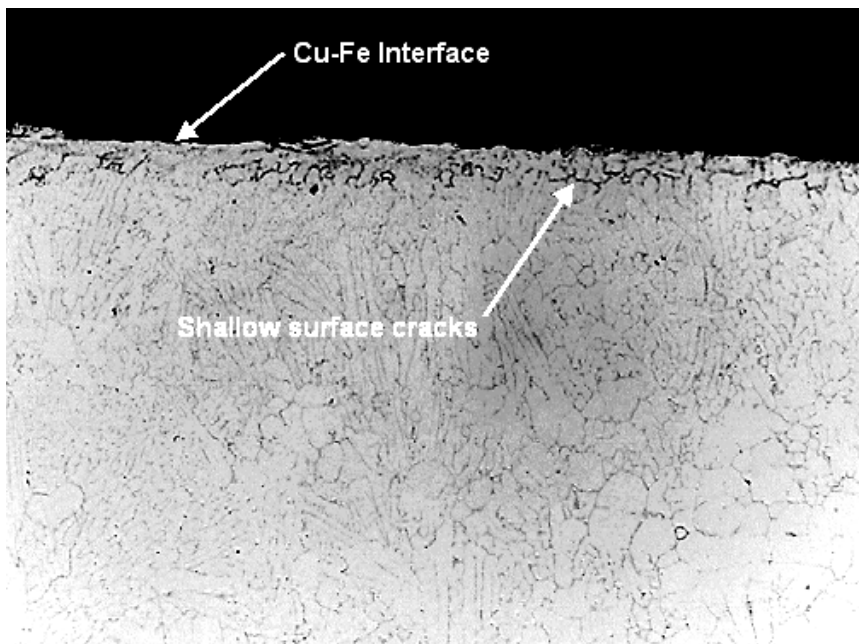
Figure 15 - Microstructure of copper-iron interface showing shallow chill zone and small surface cracks. 200X

Motor Performance with Copper Rotors

Three companies used dynamometer efficiency tests as per IEEE Specification 112, Test Method B, as required in the U.S. by the National Electrical Manufacturers Association (NEMA) and the Energy Policy Act of 1992 (EPAct). The fourth company used the IEC 34-2 test method. The first rotors were for an 15 Hp (11.2 kW) motor and were 14.5 cm (5.7 inches) in diameter with a 15.2 cm (6-inch) stack height containing 6.4 kg (14 pounds) of copper in the conductor bars and end rings. This required a 13.2 kg (29-pound) charge of molten copper to the shot sleeve. The second set of rotors for which motor test results are available were for a larger 25 Hp (18.5 kW) motor. The rotors were 16.5 cm (6.5 inches) in diameter with stack height of 24.1 cm (9.5 inches) and contained 11.4 kg (25 pounds) of copper requiring melting of 17.7 kg (39 pounds) of copper per shot. Limited data on two smaller motors was also reported to CDA by the manufacturer.

These motors were both tested 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 11.2 kW (15 Hp) 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 % lower in the copper rotors compared to the aluminum. Full load losses in the rotor were about 40% 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 either the slot design or 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 to 10 % reduction in losses are expected through rotor and overall motor design optimization.

IEEE Loss Segregation Test Results

	Watts Loss Aluminum Rotor	Watts Loss Copper Rotor	Watts Difference	Percent Difference
Stator Resistance	507	507	0	0
Iron Core Loss	286	286	0	0
Rotor Resistance	261	157	-104	-40
Windage / Friction	115	72	-43	-37
Stray Load Loss	137	105	-32	-23
Total Loss	1306	1127	-179	-14

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 one minute compared to a 20-minute air cool and would be important to manufacturing efficiency.

Motor tests of the 25 Hp (18.5 kW) 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 as an initial attempt to optimize the motor design for the high electrical conductivity of copper.

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 29% lower in the copper rotors and the overall losses were reduced by 23%. 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 for every 10-degree C decrease in motor operating temperature. With proper maintenance, motors with cast copper rotors will last longer and will be more reliable.

Tests results for this "optimized" copper motor:
- Rotor Loses   -29%
- Total Losses   -23%
- Temperature Rise   -70%
- Efficiency   +1.6%   90.9% vs. 92.5%

Stator windings and iron core were modified from standard motor design to better utilize the high electrical conductivity of copper.

A third set of rotors cast for another motor company were for a 4 Hp (3 kW) motor. The end ring was 3.54 inches (90 mm) in diameter, stack height 6.1 inches (155 mm) and contained 7 lbs (3.2 kg) of copper. Overall motor losses were reduced by 21% with the copper rotor compared to the conventional aluminum.

Copper rotors for a 5 Hp (3.7 kW) motor were cast for a fourth manufacturer. A cross-section of this rotor is shown in Figure 16. Rotor I^2R losses were reduced by 38% compared to the aluminum counterpart motor, but surprisingly, the iron core loss component was much higher for the motor with the copper rotor. This was apparently due to insufficient consideration of the rotor and stator lamination designs from the aluminum rotor used. It appears that the iron was almost totally saturated in the aluminum design. The higher current in the copper could not further magnetize the iron and appeared as a large apparent loss.

Figure 16 - Cross-section of a die cast copper rotor showing complete filling of the conductor bars.

This experience with insufficient iron in this case and in at least one other motor for which CDA provided cast copper rotors for manufacturer evaluation, prompts a general observation. Use of copper in the rotor is, as expected, a very effective way to achieve a significant increase in electrical energy efficiency. But to apply copper in the rotor before a number of other well understood approaches to improving motor efficiency are introduced generally is not sensible. One of these is application of high quality, low loss iron in both the stator and rotor laminations. A good deal of attention should be given to taking advantage of low loss silicon electrical steels and to ensuring that the magnetic paths in the rotor laminations have sufficient iron to respond to the higher magnetizing forces characteristic of the high conductivity copper conductor bars.

OPTIMIZING ROTOR DESIGN FOR COPPER

Introduction

Motor tests to characterize performance of copper rotors were done for the most part with rotor laminations and slot designs designed for aluminum rotors then in production by the several participating motor companies. While this straight forward substitution of copper for aluminum showed very substantial reduction in losses and increases in motor efficiency, designing the motor as a whole and the shape of the rotor bars in particular for the high conductivity of the copper in the squirrel cage, would be expected to further enhance motor performance. The more complete description of the performance of the 15 Hp (11.2 kW) motor discussed above shows that substitution of copper for aluminum into laminations designed for aluminum results in an undesirable

drop in starting torque and an increase in in-rush current [3, 4]. CDA has initiated a design study by Professor James Kirtley at the Massachusetts Institute of Technology to provide the theoretical underpinning and method to design motors for the copper rotor. This work is ongoing. An outline of the approach follows.

At first it seems that the substitution of copper for aluminum in induction motors would be straight forward. The higher conductivity of copper should make for higher motor efficiencies. It is not quite that simple, however. Consider the simple induction motor equivalent circuit shown in Figure 17.
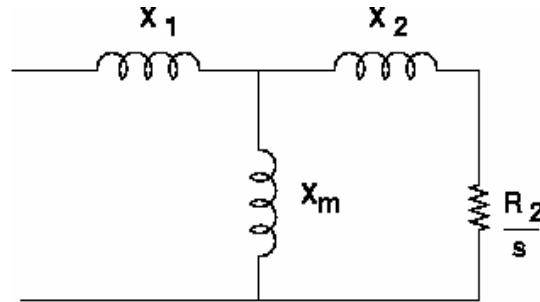

Figure 17 – Simple induction motor model.

The value of the rotor equivalent circuit resistance R_2 is inversely proportional to the conductivity of the cast rotor material. It is straight forward to estimate a torque-speed curve using this sort of model and an example is shown in Figure 18. Shown are two hypothetical torque-speed curves. The difference between the two is the value of the rotor resistance R_2. The curve that represents lower rotor resistance is to the right in the low "slip" region, indicating that it would run at lower slip (and so higher efficiency). On the other hand, it also exhibits lower starting torque.
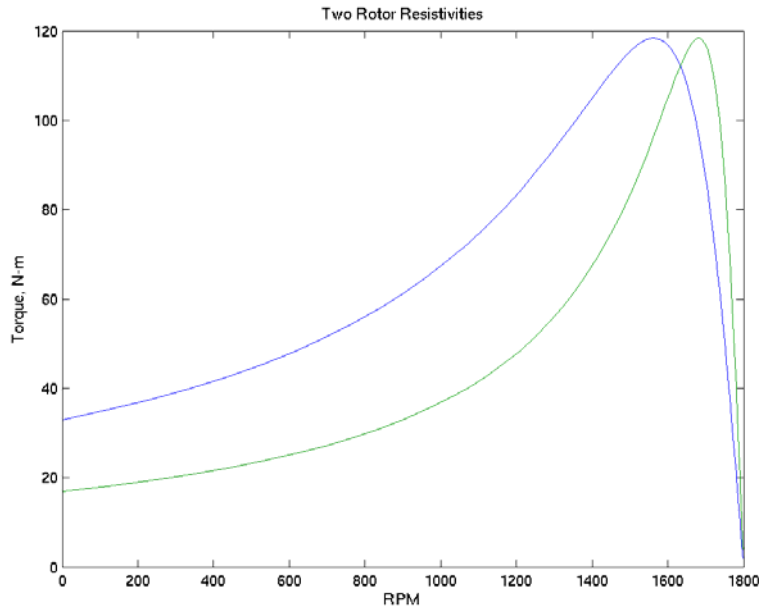
Figure 18 - Torque speed curve as influenced by rotor resistance
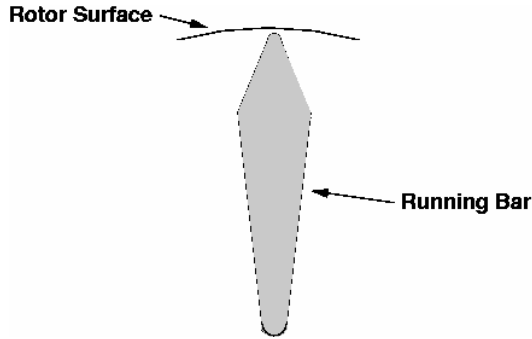
Figure 19 - Aluminum bar
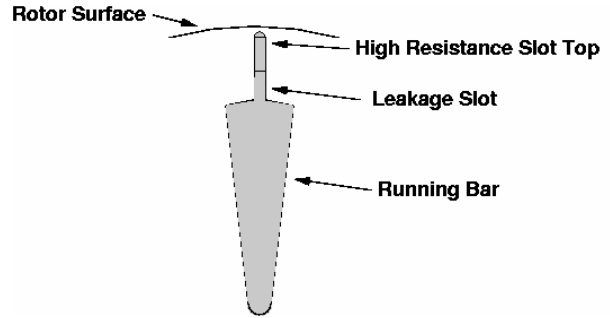
Figure 20 - Copper rotor bar.

Using the Skin Effect

The high conductivity of copper allows the rotor designer to use the 'skin effect' to tailor the behavior of the rotor to improving motor performance. For example, when the motor is running, its slip is small and rotor frequencies are low (on the order of 1 Hz).

When the motor is starting the rotor is nearly stationary and electrical frequency seen by the rotor conductors is higher (about line frequency). Consequently the apparent rotor resistance can be higher. We might illustrate two ways in which motor designers have attempted to take advantage of this effect.

Shown in Figure 19 is the shape of a typical conductor bar as it would be cast into an integral horsepower motor. The bar has a taper to accommodate the shape of iron rotor teeth (they must be of enough width to carry flux and so are roughly rectangular). The bar is tapered toward the rotor surface, probably to make the magnetic aspect of the rotor surface more continuous.

One way of making eddy currents in the rotor work to increase bar resistance at high frequency (as in starting) would be to shape the bar as is shown in Figure 20. This is the shape of a copper bar intended to replace the aluminum bar of Figure. 19. All that has been done is to cut away some of the material above the widest part of the bar, making the top of it a narrow projection toward the rotor surface.

Frequency Response

To understand how these different rotor bar structures might work, we have calculated the frequency response of their impedance per unit length. The apparent bar impedance is shown in Figure 21 for both of the bars shown in Figures 19 and 20.
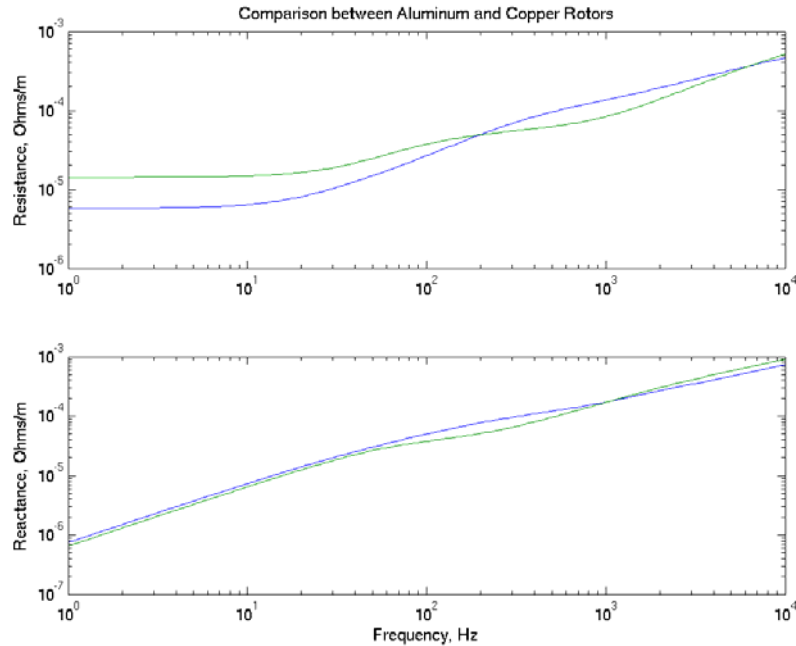
Figure 21 - Rotor impedance bar

As can be seen, the copper rotor has lower resistance at low frequency, corresponding to running conditions but higher resistance at higher frequencies. In this particular case, however, the resistance at starting conditions (60 Hz) is not actually higher for the copper bar. It does have higher resistance at frequencies well above 60 Hz, however, and thus will cause higher stray no-load and load losses.

Stray Loss

All induction motor stator windings produce magnetic flux density which is not strictly sinusoidal. Deviations from purely sinusoidal waveforms are generally described as 'space harmonics', referring to components of the Fourier Series for the shape of the magnetic flux density. Three phase windings produce fifth and seventh space harmonics and these produce excitation to the rotor at approximately sixth harmonic frequency (360 Hz for 60 Hz motors). There are also important variations from pure sine waves at harmonic order about that of the number of stator slots per pole pair (for the four-pole, 36 slot motors we are considering, those excitations are at about 1,080 Hz). Higher resistance at those frequencies will produce higher stray load and no-load loss in a motor.

Shown in Figure 22 is a comparison of predicted torque/speed curves for motors built with cast copper and aluminum rotor cages. Both motors have about the same starting torque. As can be seen, the aluminum rotor machine has higher breakdown torque because of the higher leakage impedance of the copper rotor machine (due to that narrow upper slot portion). The copper rotor machine appears to have lower running slip, but this is, as it turns out, offset by higher stray load losses due to the higher resistance at high order harmonic frequencies. These motors have almost identical performance.
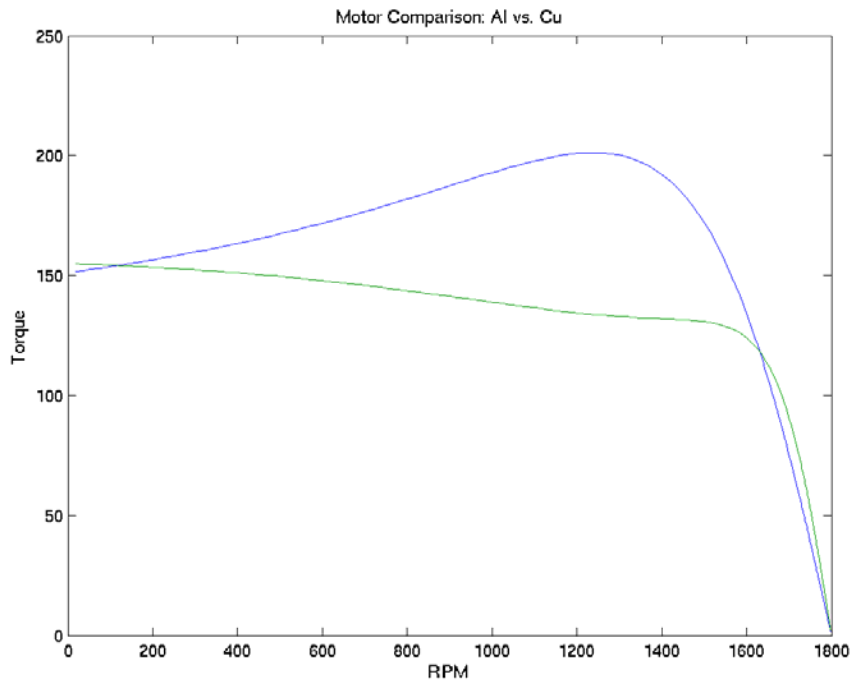
Figure 22 - Copper vs. aluminum.

Alternative Rotor Bar Designs

Another way of making a rotor bar shape is shown in Figure 23.
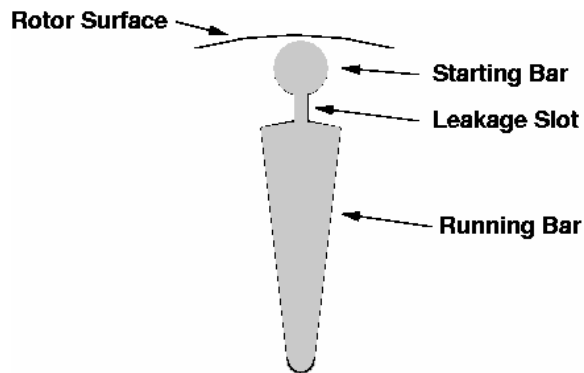
Figure 23 – Alternative copper rotor bar.

The bar shown here has a relatively large rod of copper near the surface, a narrow slot which produces magnetic leakage below that and then the main 'running' part of the bar below. This bar will produce relatively high starting resistance, low running resistance, and resistance at high harmonic frequencies which is not unreasonably large. A comparison of two rotor impedances is shown in Figure 24.

These two rotors have similar running resistance but one has higher starting resistance and lower resistance to high order harmonic currents.
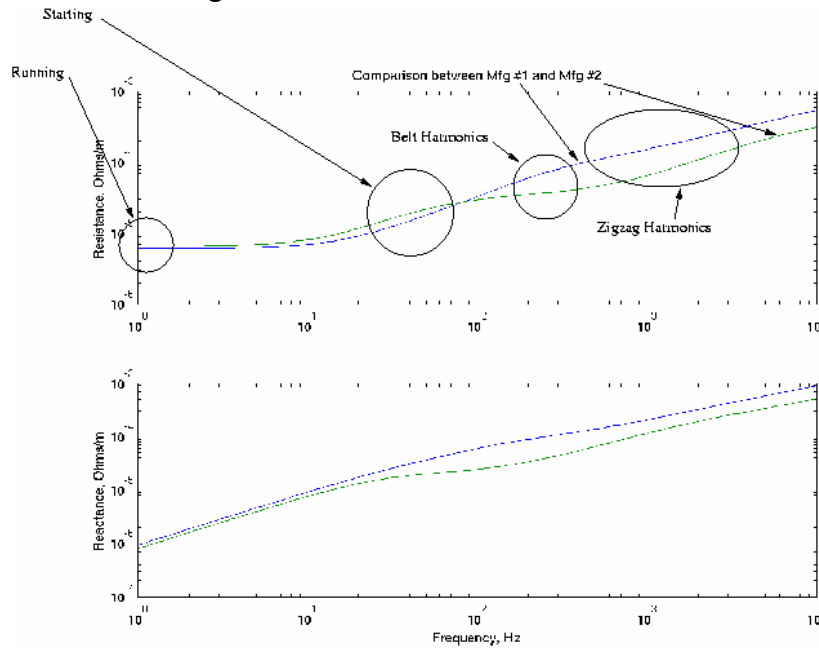
**Figure 24 - Comparison of two copper rotor bar impedances.**

BEST PRACTICES FOR LARGE COPPER ROTOR PRODUCTION

For successful pressure die casting of copper motor rotors, use of practices developed in the first phase of the project will be critical. These are summarized as follows:

1. The high melting temperature of copper (1083°C) requires that high temperature, high performance die materials be used. Conventional die steels such as H-13 lose strength rapidly at the operating temperature that is well above the tempering temperature. Mold materials that have phase transitions in the service temperatures range are known to have substantially decreased fatigue strength. High temperature materials found suitable for dies include the tungsten alloy Anviloy 1200 as well as the forged and solid solution strengthened nickel-base alloy INCONEL alloy 617 and Haynes alloy 230. INCONEL alloy 625 was also shown to be promising, but the Haynes alloy 230 is currently the recommended die material. Compositions and suppliers of candidate die materials are listed below.

2. To obtain extended die life and avoid premature failure by thermal fatigue of the surface, it is absolutely essential to preheat and to operate the dies at elevated temperature. The optimum temperature range to heat the dies to is 625 to 650°C. 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 the thermal fatigue of the surface that leads to crazing and cracking. Schematic diagrams of the

tooling for the horizontal pressure die casting of copper motor rotors are presented in Figures 25 and 26. Heater and insulation placement in and behind the die inserts are shown in Figure 25. The die designer responsible for this novel heated die engineering and sources for the resistance heaters and insulation material are listed below.

3. Use of shot-by-shot induction melting of copper is a practical and advantageous alternative to gas fired melting in a large volume furnace, as is the practice for aluminum, and is a good method for casting small numbers of rotors or for development work. Melting the copper one shot at a time greatly minimizes exposure of the molten copper to air and the resulting oxygen pick-up. Dipping from a large furnace and transfer of molten copper to the shot sleeve is much more problematic with the high melting metal than these same operations with aluminum. A large furnace of molten copper would result in an uncomfortable environment for machine operators and be subject to substantial oxygen pick-up. Use of carbon to protect the melt from oxygen is possible, but then the operator must be aware of the potential for a very low oxygen copper melt to pick up large quantities of hydrogen, especially in a humid shop environment. Shot-by-shot melting for small numbers of rotors has the advantage that the induction melting coils and power supplies can be sized to melt the copper in a time consistent with the overall machine production cycle. Use of a double coil alternatively switched to the power supply allows for efficient charging, pouring, and use of the power supply. Figure 27 shows the double induction furnace used in the development work at Formcast.

4. For extended production of copper rotors, induction melting of copper in enclosed furnaces under a protective nitrogen atmosphere has now been shown to be a sound approach. Copper melt stock can be fed continuously to the furnace as wire rod through appropriate seals or as scrap, cathode or ingot through a door equipped with a seal. Molten copper is fed directly to the shot sleeve through a refractory tube extending through the furnace shell below the melt surface. Pressurization of the enclosure forces molten copper up through the tube similar to the feeding method common to low pressure die casting machines. A supplier of this equipment is listed.

5. A heated shot sleeve surrounded by a thermal wrap is very helpful in maintaining sufficient heat in the molten copper charge to ensure complete filling of the rotor cavity and in reducing thermal fatigue. A replaceable center insert at the point of pour into the shot sleeve allows for convenient replacement of this high wear area. DieTec designs for replaceable shot sleeve inserts are shown in Figure 28. Use of a nickel-based alloy for the shot sleeve will be very helpful in production.
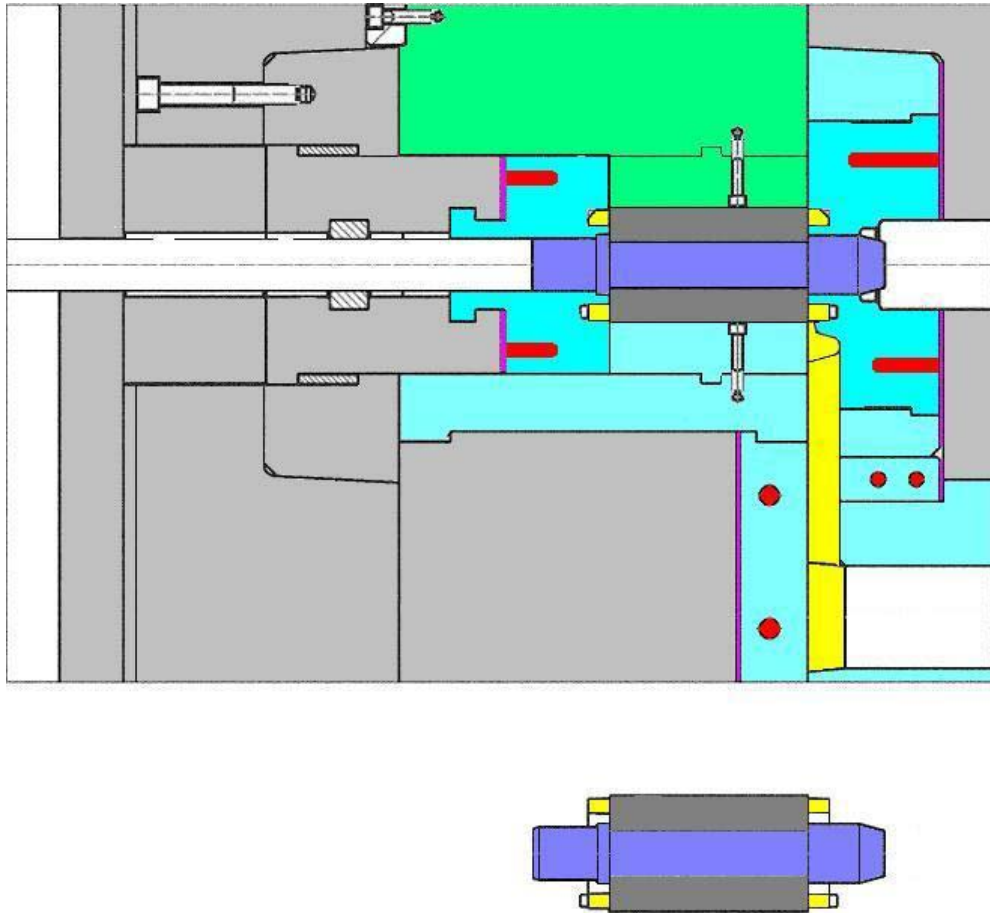
Figure 25 - Horizontal pressure die caster with tooling for rotor casting in closed position. The arbor (dark blue) and the steel rotor laminations (dark gray) are shown in the detail beneath and in position in the machine. Copper from the shot sleeve biscuit, runner and end rings are shown in yellow. 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 that 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)
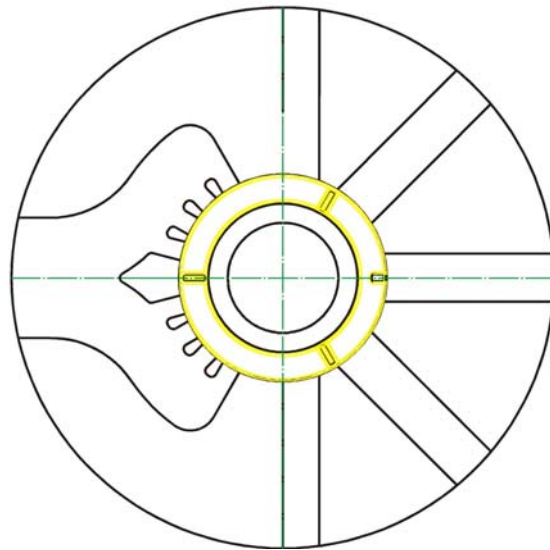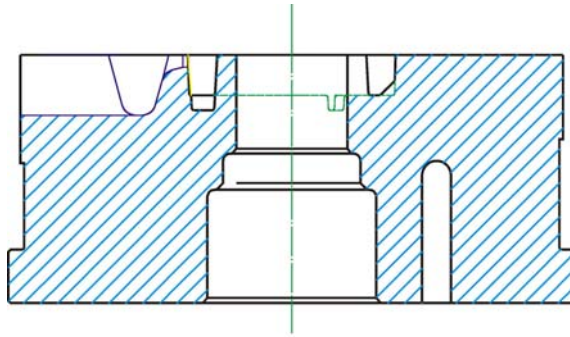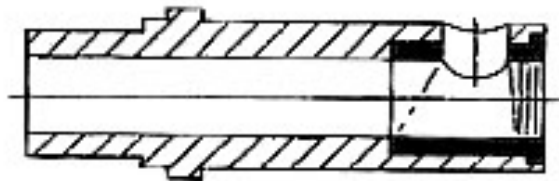
Figure 26 - Diagram of end ring die showing eight gate locations from the runner bar. (Courtesy of DieTec GmbH).
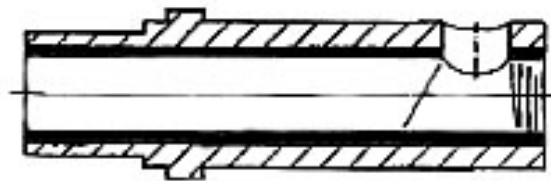
Figure 27 - Transfer of single shot of molten copper from double coil induction melting unit to shot sleeve in the CDA development work at Formcast.
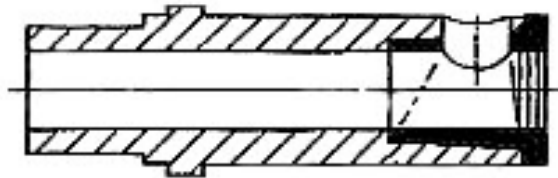
Shot Sleeve with inserted partial, conical wear
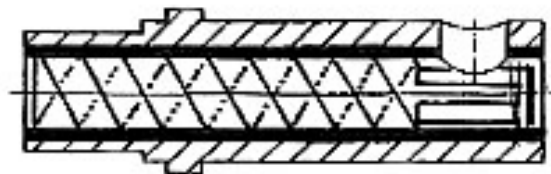lining (pouring shot section)

Shot sleeve with tight-shrunk partial,
cylindrical wear lining (pouring shot section)

Shot sleeve with tight-shrunk complete
cylindrical wear lining (full length)

Shot sleeve with tight-shrunk complete cylindrical
wear lining (full length) and inserted cooling system

Figure 28 – DieTec designs for shot sleeves with replaceable inserts.

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5. D.T. Peters, S.P. Midson, W.G. Walkington, E.F. Brush, Jr. and J.G. Cowie: Porosity Control in Copper Rotor Die Castings: Trans. the North Amer. Die Casting Assoc. Congress, Indianapolis, IN, 2003.

NOMINAL COMPOSITIONS OF CANDIDATE DIE ALLOYS (wt%)

Anviloy 1200			TZM Molybdenum	
W	90		Ti	0.5
Ni	4		Zr	0.09
Fe	2		C	0.025
Mo	4		O	0.025 max
			H	0.005 max
			Mo	99.25 min

Nickel-base alloys: Inconel and/or Haynes Alloy Designations

(Alloy)	601	617	625	718	754	230
Ni	60.5	44.5 min	58 min	70 min	78	47.3
Cr	23	22	21.5	15.5	20	22
Al	1.35	1.15	0.4 max	0.7	0.3	0.3
Ti	-	-	-	2.5	0.5	-
W	-	-	-	-	-	14
Co	-	12.5	1.0 max	1.0 max	-	5 max
Mo	-	9	9	-	-	2
C	-	0.1	0.1 max	0.08 max	0.06	0.1
Nb	-	-	3.65	0.95	-	-
Fe	-	-	5 max	7	1	3 max
Y	-	-	-	-	0.6	-
Si	-	-	-	-	-	0.4
Mn	-	-	-	-	-	0.5
La	-	-	-	-	-	0.02

SELECTED MECHANICAL PROPERTIES OF CANDIDATE DIEDALE T. PETERSPAGE 354/12/2004CREATED ON 3/30/2004 1:55 PMLAST PRINTED 4/12/2004 9:09 PM ALLOYS

	Temperature (°C)	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Haynes Alloy 230				
Sheet	20	862	345	48
	650	669	269	55
	1095	117	57	50
INCONEL alloy 617				
Sheet	20	759	352	58
	650	565	214	69
	1095	110	55	56
INCONEL alloy 625	20	903	490	49
Sheet	650	759	372	56
	1095	97	39	45
INCONEL alloy 601				
Hot finished plate	20	772	448	40
annealed	650	482	310	33
	1177	28	15	14
INCONEL alloy 718				
Hot rolled 10 cm round				
annealed and aged	20	1358	1131	17
	650	1324	1138	19
INCONEL alloy MA 754				
Annealed bar	20	965	565	20
	650	565	345	22
	1177	115	110	15
Anviloy 1200	20	1034	965	2.0
	650	869	-	1.0
	1095	239	-	3.5
TZM	20	552	482	5.0
80 to105 cm				
stress relieved bar				

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Die Design Expert

Mr. Ruedi Beck
DieTec GmbH
Bedastrasse 39
CH 9200 Gossau
Switzerland
Tel: +41 (0)71 388 20 30
Fax: +41 (0)71 388 20 31
Email: info@dietec.ch

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