Porosity Control in Copper Rotor Die Castings

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Abstract

This paper reports on the results of an investigation to minimize and control the distribution of porosity in edge-gated copper rotor die castings. A Flow 3-D computer modeling exercise was used to simulate shot profiles that result in formation of large pores in the end rings, as well as to predict improved profiles that will reduce or eliminate the residual porosity. These model results were then tested by die casting a series of copper rotors using an existing edge-gated rotor die set on a Buhler 750-ton real time shot controlled die casting machine. Shot profiles are shown to be very instrumental in controlling porosity. Profiles designed to pre-fill a portion of the gate end ring at the slow shot speed prior to accelerating to the fast velocity to fill the conductor bars and ejector end ring are shown to be very effective in minimizing and controlling porosity and to achieve a fairly uniform distribution of small pores present largely in the end rings. Thermal management of the entire system is also important to casting quality including metal superheat, and shot sleeve and die temperatures.

Introduction

High pressure die casting is the most economical process for production of a variety of complex parts because of its ability to achieve high production rates, final shape with little machining required, excellent surface finish and adequate properties for many applications. Certainly these advantages are important to producing the squirrel cage rotor structure of the induction motor rotor whether cast in aluminum or copper. The high rate of introduction of liquid metal through the gates into the die cavity filled with air generally results in some distributed porosity in the structure. As reported at the 2002 Die Casting Congress, die-cast copper motor rotors built into motors and tested by motor manufacturers showed little evidence that porosity in the end rings or conductor bars was an issue.[1] Rotors were easily balanced and required little in the way of balancing weights. Porosity in the far end ring of copper rotors appeared to be 2 to 3 percent but did not extend into the conductor bars. Motor electrical tests consistently showed a 30 to 40 percent reduction in rotor I^2R losses and overall losses reduced by 14 to 23%. There was remarkable consistency in rotor-to-rotor results. Low stray load losses determined in the IEEE Standard 112B test indicated no significant porosity in the conductor bars of the copper rotors tested. In subsequent work, a set of larger rotors tested by a motor manufacturer was difficult to balance. Sectioning of the end rings revealed large porosity especially in the end ring at the ejector end showing as much as 25% voids in some castings and about 8 to10% voids in the rotors selected for electrical tests. Therefore, additional work, reported in this paper, was carried out to determine the origin of the porosity. Both modeling and experimental casting trials were performed to determine the process conditions required to significantly reduce porosity to acceptable levels.

Modeling Study

Flow 3D software using computational fluid dynamics methods was used by Walkington Engineering to model the metal flow to simulate metal flow conditions. Review of the flow videos and other data from the simulations were used to evaluate the conditions that would cause large pores in the end rings and conductor bars and to identify process conditions that would eliminate the large porosity conditions. These simulation methods were viewed as being a less expensive and less time consuming way to find the optimum conditions than an extended series of die casting trials. Selected predictions from the modeling simulations were tested by making a few experimental castings. The model predicted the location of the larger trapped bubbles. The objective was to find operating conditions that will eliminate these. The die-cast copper shape modeled is shown in Figure 1.

The part consists of an end ring at the gate end and an end ring at the ejector end connected by a series of conductor bars. The bars are formed by channels through the stack of punched iron rotor laminations (Figure 2). Thus the lamination stack plays the role of the die for the conductor bars.

The part is edge gated with four approximately semi-circular gates on each side of the vertical runner. In the die used to produce copper rotors, the cross sectional area of the gates is 80% of the runner cross section. Several different gating systems were examined by modeling them and simulating flow conditions to see if they would reduce porosity. None of these alternative gating systems, which included larger solid gates to eliminate the reduced gate area, caliper gates to redirect flow entering the gate end ring and tapered pin gates, showed any benefit, at least within the limited set of parameters tested, and are not discussed in this paper.

Most of the emphasis in the modeling study discussed here involves variation in the plunger position – speed profile (shot profile). Two approaches were examined. The first relies on die casting experience to the effect that, while at high speed there is much turbulence as metal enters the gate and beyond (atomized flow), this turbulence results in a proliferation of very small and widely dispersed pores but generally tends to keep the large bubbles from forming. This situation was considered to be of much less concern than having a few large bubbles or voids. A problem with this approach is the high metal velocity through the gates which may result in excessive erosion and short die life, especially when die casting copper at 2200ºF or above.

A second approach examined was to have the molten metal approach and pass the gates at a relatively slow speed and pre-fill the gate end ring to some extent before increasing the plunger speed to fill the rest of the die cavity. The idea here was to minimize the turbulence initially so that the air is pushed ahead of the molten metal front to the vents located on the gate end ring, thereby reducing the trapping of air and formation of large pores. In this case, the slow initial fill could result in freezing at the gates and an incomplete fill. This was thought to be a manageable problem with the die system developed for casting the copper motor rotor. The die system developed for extending die life while die casting copper uses nickel-base alloy dies that are first preheated and then operated in the temperature range 1160 to 1200ºF with heat supplied by electrical resistance cartridge heaters.[1] The high operating temperature greatly minimizes the temperature and strain gradients between the die surface and its interior that lead to heat checking and die failure. These hot dies allow a somewhat longer casting cycle. A schematic of this die system is shown in Figure 3.

Simulation of the Base-Line Shot Profile

Sectioning of the end rings from a 15 Hp motor die-cast copper rotor produced with the shot speed profile of Figure 4 and Table 1 often resulted in the inclusion of a number of large voids as shown in Figure 5. A modeling run was done to determine if the void pattern could be predicted.

Basically this profile extends the slow shot so that it will pre-fill about 10% of the gate end ring before the fast shot speed is reached. Results are shown as frames from Flow 3D videos. (Note that symmetry of the part allows a simulation to be done on half of the model thereby reducing computer run time.) It is important to note that these videos show only the skin of the casting which is shown next to the cavity wall and surrounding any bubbles present. Thus the casting appears empty where there actually is metal. The videos are then examined for the skin formation around air bubbles. Porosity was judged by the estimated bubble content of the gate end ring, the ejector end ring and the conductor bars. The fill time for a given model (which includes a small amount of time in the runner) is reported as this is an important factor in controlling surface quality, and is an issue in terms of premature solidification.

Figure 6 shows the simulation for the gate end ring using this base-line shot profile. The arrows show the predicted porosity in about the same locations as seen on the sawed cross section of Figure 5. Figure 7 shows the simulation for the ejector end ring. There are no large bubbles, but there is considerable trapped air in the bars (arrows) that will get pushed into the end ring later in the fill. There is some bubble formation in the end ring, but no bubbles as large as would be expected from the porosity actually found to be present. The results seem to verify that the simulation is predicting the porosity condition actually observed in the end rings. However the simulation apparently predicts some air trapped in the conductor bars because this is the last point to fill, although no large bubbles were shown at this location by the simulation. Machining by turning a number of rotors ODs to the point of largest bar thickness invariably showed essentially pore-free conductor bars with only a few pin head size pores found (see Figure 8). This apparently explains the excellent properties of motors built with copper rotors, in particular the low stray load loss component. We conclude that the trapped air in the bars seen in the videos is actually in the form of small dispersed bubbles.

20% Pre-fill Simulations

Two simulations were done with a slow pre-fill to 20% followed by rapid acceleration. In the first case, a very fast speed of 450 cm/sec. was used for the fast shot (Figure 9 and Table 2). The fill time was a rather long 296 msec. because of the slow pre-fill. Figure 10 shows the model simulation with the gate end ring almost full. No bubbles are present although the area at the arrow might develop some porosity. The ejector end ring also appears to be pore-free (Figure 11) at this point in the shot, although the simulation suggests that there would be some trapped air in the conductor bars. This shot profile appeared to be promising. Bubble formation in the end rings, although not eliminated, had been reduced to one medium sized bubble in the gate end ring and one fair size bubble in the ejector end ring.

Another simulation run at 20% pre-fill was done to try to eliminate the trapped air in the conductor bars. It appeared from the videos of the previous run described in the last paragraph that the metal would flow rapidly down the gate ring and flow into the bars further away from the gate at a higher flow rate than for the bars closer to the gate. The bars further from the gate would catch up and pass the bars closer to the gate trapping air in the bars. The concept behind this new run was that a slower acceleration to the fast shot speed would allow more time to develop the flow in the bars adjacent to the gate. In the previous run, the acceleration from the initial speed to the final fast shot was extremely rapid. It was hoped that a slower acceleration would give good end rings and reduce the apparent porosity in the conductor bars. The speed was increased at the end to compensate for the slower acceleration, but the fill time was still long at 343 msec. The shot profile is pictured in Figure 12 and Table 3.

The concept of the slower acceleration did not function as hoped and in fact made things worse. Although there appeared to be no trapped air in the bars, large pore formation in both end rings was more pronounced.

Delayed Transition with 40% Pre-fill

Finally in this simulation sequence, a pre-fill shot profile with a delayed transition from slow to fast shot was used (Figure 13 and Table 4). The pre-fill was increased to 40%. The objective was to accelerate while the metal was filling the gate end ring because some early simulations had shown that a completely slow fill generated large bubbles later in the fill cycle. This strategy was quite successful. Several frames of the video showed an incipient bubble in the gate end ring but this never completely formed as was shown a few milliseconds later in the fill in Figure 14. A few small bubbles are seen but the objective was to eliminate the large bubbles. The ejector end ring was equivalent to the best in other runs and showed no large bubbles. There was no apparent trapped porosity in the bars.

This simulation work shows that there are shot profiles that predict substantially reduced formation of large trapped air bubbles and porosity. Other combinations could of course be tried that might further improve the situation. For example, a little slower pre-fill with the acceleration dragged out some during the gate ring fill would be an interesting shot profile.

Experimental Verification of Simulation Predictions

Experimental Details

The plan was to cast copper rotors to verify the predictions from the Flow 3D simulations. A number of 5.7 in. diameter by 5.25 in. high lamination stacks using the lamination design of Figure 2 were available. The 750-ton real time shot control Buhler horizontal die casting machine at Formcast Development, Inc. was used. The die used for the trials is a commercial two-plate rotor die, edge gated, with a vertical core pull to assist with rotor stack insertion and ejection of the die-cast rotor. Copper in the form of chopped C10100 wire rod was melted on a shot-by-shot basis using a push-up crucible induction furnace and a 60 kW power supply. The shot weight was 24 to 26.5 lbs. A nitrogen cover was used to prevent excessive oxygen pick-up during melting. The heated nickel-base alloy die set shown in Figure 3 was not available for these trials, so instead an H-13 die set was used.

The end ring die heating was done with a circulating oil heater augmented by direct heating with a propane heater. Achievable die temperatures measured prior to each shot at six points on the die faces ranged from 240 to about 600ºF. This is much colder than die temperatures now being used for commercial production of copper rotors which are operated at about 1200ºF to achieve long die life.. The shot sleeve was preheated by a band heater and a propane torch but the temperature was not monitored in all tests. In production, plans call for a resistance heated and insulated shot sleeve capable of reaching quite high temperatures to minimize chilling of the molten copper charge.

The machine was programmed for all of these casts to advance the plunger in the slow shot region from 26 to 50 cm/sec. and then to accelerate rapidly to 400 cm/sec. The acceleration to the fast shot speed occurred either in the runner prior to the gate or after pre-filling the gate end ring. A final metal pressure of 13,250 psi. was reached in the pressure control portion of the shot.

Effect of Melt Superheat

Prior to examining the impact of pre-fill on rotor quality, it was necessary to identify optimum casting parameters. One parameter that was found to significantly impact rotor quality was the superheat of the copper melt. A series of casts were run using a pre-fill of 55%, in which the melt temperature was increased in steps.

Figure 15 shows the gate end ring sections for melt temperatures of 2400, 2490, 2580, and 2670ºF. There is a steady improvement with increasing melt temperature with no large pores visible on the gate end ring cast at the highest temperature. Obviously 2670^{o}F is an extremely high melt temperature and the authors do not expect that such superheats would be required for commercial production. As noted earlier, commercial die sets for the casting of copper rotors require that the nickel-based die inserts be pre-heated to about 1200°F, and experience with these dies indicated that lower melt superheats are sufficient to obtain adequate part quality. However, the results from this study clearly indicate that heat loss from the liquid copper to the cooler shot sleeve, die inserts and lamination stack must be controlled in order to minimize porosity in the die cast rotors.

Effect of Die Pre-fill

Experience had verified the model simulations that acceleration to the fast shot speed before the metal reaches the gates invariably resulted in the formation of large pores in both end rings similar to the cross sections of Figure 5. In the final set of three casting trials, the amount of pre-fill of the gate end ring was varied. The shot profile was varied so the speed transition occurred below the gates about half way up the runner, and at pre-fills of 33% and 55%. The conditions and shot profiles were otherwise as described above except that the shot sleeve was heated to a higher temperature of about 840°F. Due to the high super-heat used in the tests, temperature measurement of the melt was an issue, with the available thermocouple system unable to measure much above 2350°F. An estimated melt temperature of 2600°F was reached by removing the thermocouple and continuing heating for 56 seconds past 2350°F. The results are shown as the sawed cross sections of Figure 16. Clearly the porosity decreases markedly with pre-fill compared to acceleration before the metal reaches the gate and is further reduced at the higher pre-fill. This same series run with a melt temperature of 2400°F showed considerable porosity with and without pre-fill. We conclude that, in the die set used in these experiments, the incidence of large pores in the end rings is reduced with increased melt temperature and with some degree of pre-fill. Presumably the pre-fill cannot be increased indefinitely with further increase in part quality. Additional experiments to determine this limit should be undertaken.

Conclusions

The work reported in this study shows the utility of computer flow simulation in identifying die casting operating conditions that lead to formation of large pores in the castings and to predict shot profiles that will significantly minimize or eliminate large pores caused by trapped air. Simulation showed that operating conditions in use at the time for developmental studies of die casting the copper motor rotor were likely to result in large pores as observed. Simulation predicted that changing the shot profile so as to pre-fill the die cavity beyond the gates to some extent before acceleration of the plunger to the fast speed would largely eliminate the incidence of large pores in the end rings of the rotor. Experimental work verified that pre-fill was effective in eliminating the large pores. The importance of having adequate superheat in the melt was also shown to be an important factor in minimizing porosity. Rather high melt temperatures were required for casting in the H-13 dies available for this study. Commercial production of copper rotors uses nickel-base alloy dies operated at 1200°F and an insulated and heated shot sleeve operated at a similar temperature. Less superheat is required with this equipment.

Acknowledgement

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References

1) D.T. Peters, J.G. Cowie, E.F. Brush, Jr. and S.P. Midson, “Use of High Temperature Die Materials and Hot Dies for High Pressure Die Casting Pure Copper and Copper Alloys”, Proceedings of the 2002 Die Casting Congress, Rosemont, IL Sept. 30 – Oct. 2, 2002.

Listing of Figures with Captions

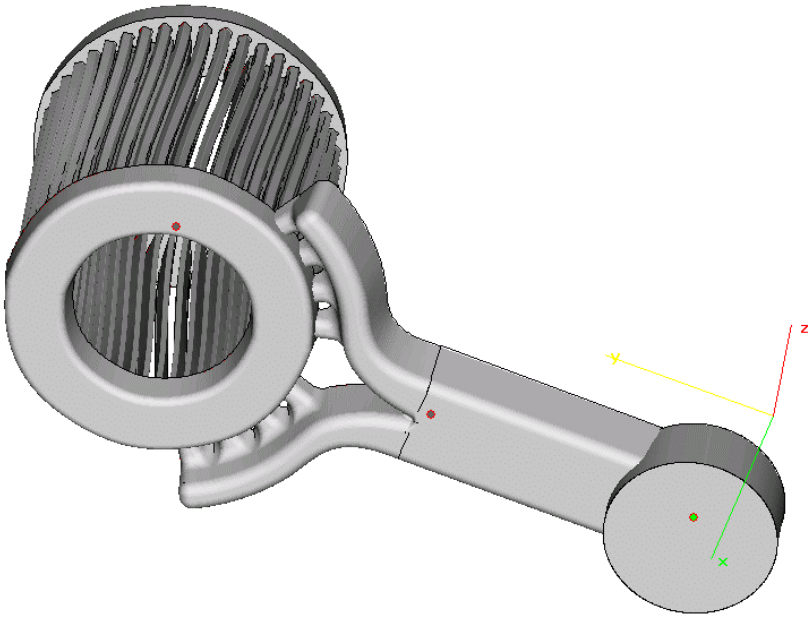


Figure 1 – Model of Rotor Squirrel Cage with Gates and Runner.

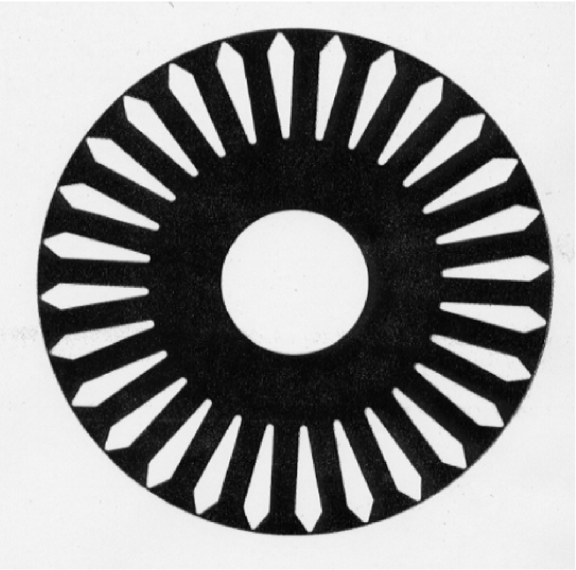


Figure 2 – Rotor Lamination for a 15 Hp Motor – Designed for Aluminum Cage.

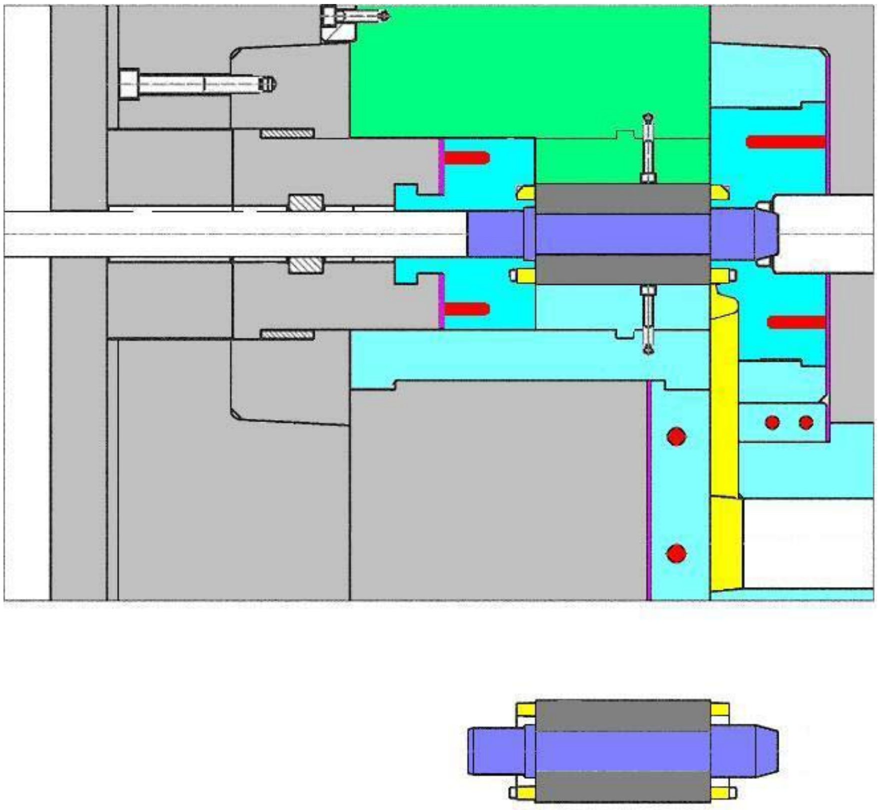


Figure 3 – Schematic Diagram of Heated Nickel-Base Alloy Dies for Rotor Die Casting. The arbor (dark blue) and the steel laminations (dark grey) are shown as assembled in the insert

below and in position in the machine. Copper in the biscuit, vertical runner and end rings is shown in yellow. The nickel alloy end ring inserts and runner die components are shown in medium blue with electrical resistance heaters in red. These components are backed with insulation (pink). The vertical core pull is shown in green and the steel platens in light grey. *(Courtesy of DieTec, GmbH).*

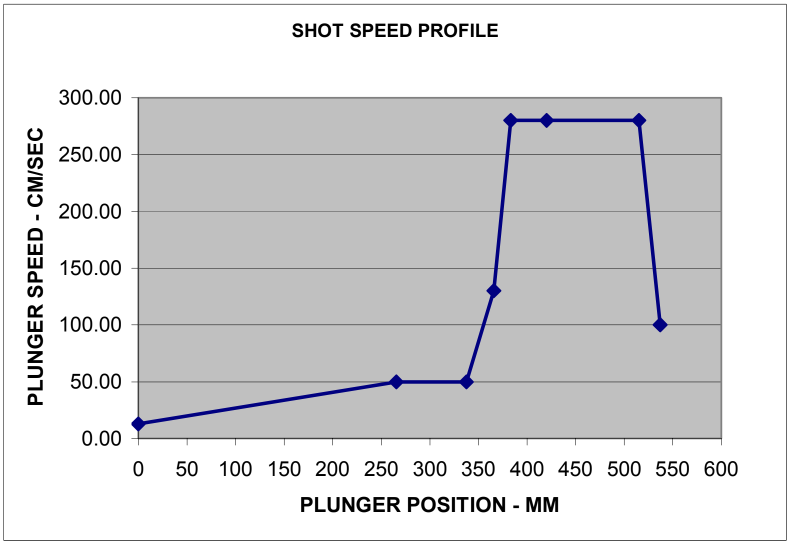


Figure 4 – Shot Speed Profile Used in Simulation of Baseline Die Castings of Copper Motor Rotors.

Figure 5 - Photographs of Sectioned End Rings from Copper Rotors Typical of Baseline Casting Conditions.

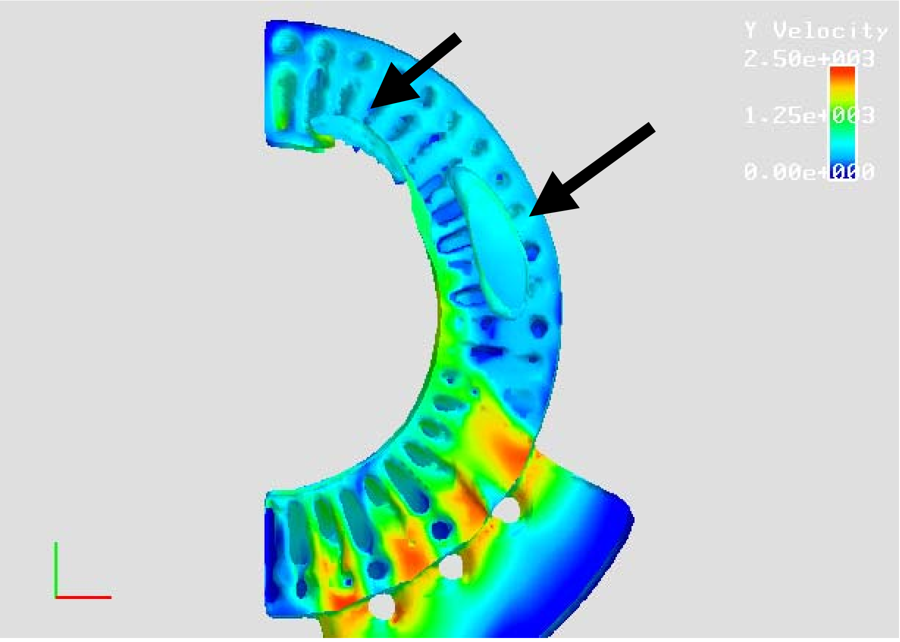


Figure 6 – Simulation for the Gate End Ring Using the Baseline Settings Used for Copper Rotor Production.

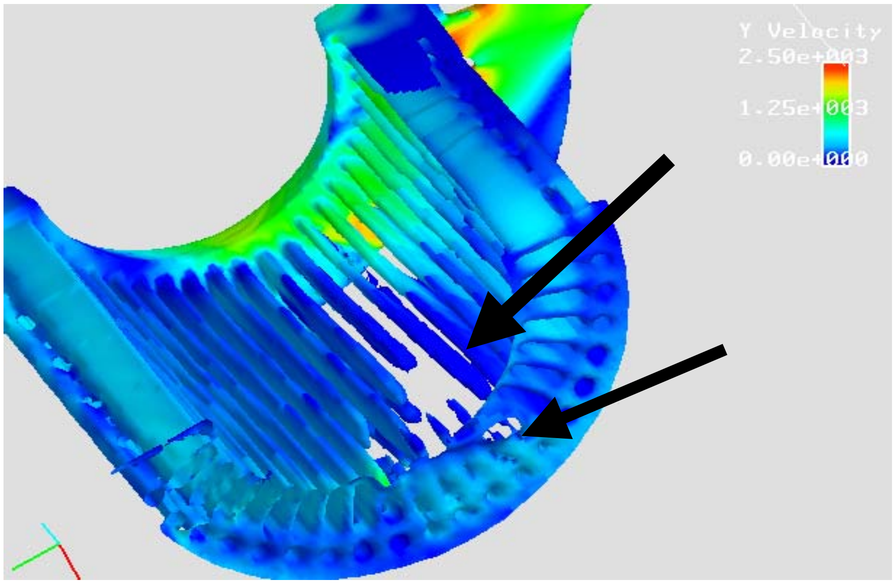


Figure 7- Ejector End Ring from the Same Simulation.

Figure 8 – 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.

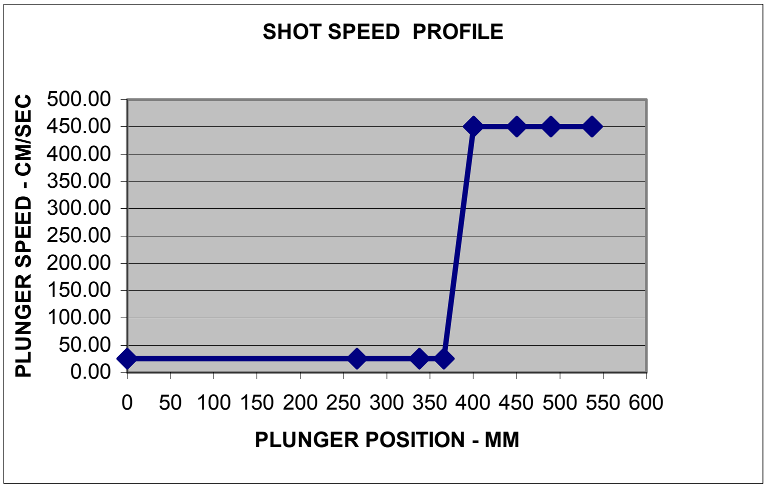


Figure 9 – Shot Speed Profile Used in the Simulation of 20% Pre-fill before Switching to the Fast Shot Speed.

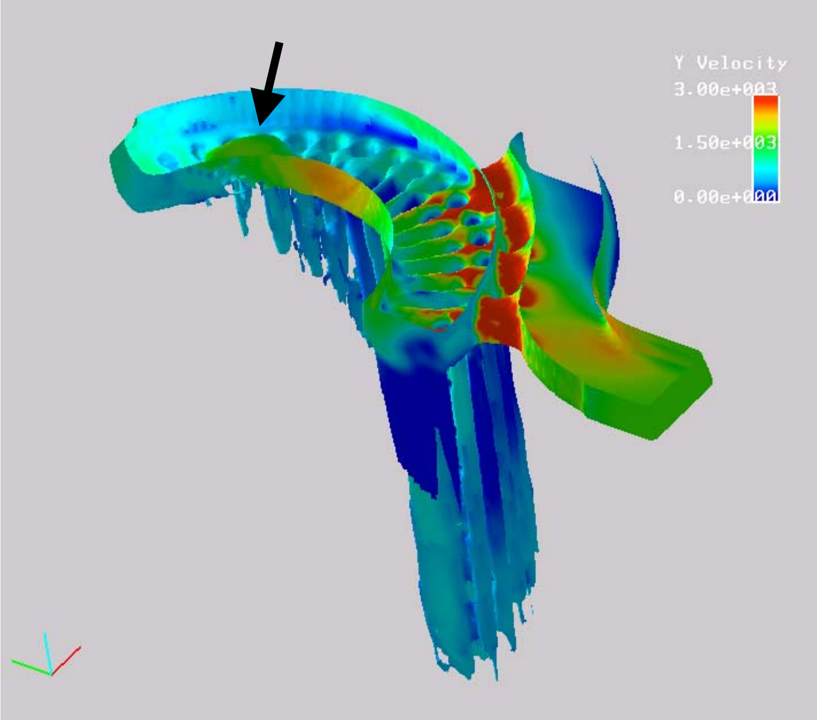


Figure 10 – 205 Pre-fill Simulation.
Gate end ring is almost full. No large bubble porosity
Although area by the arrow might develop into porosity.

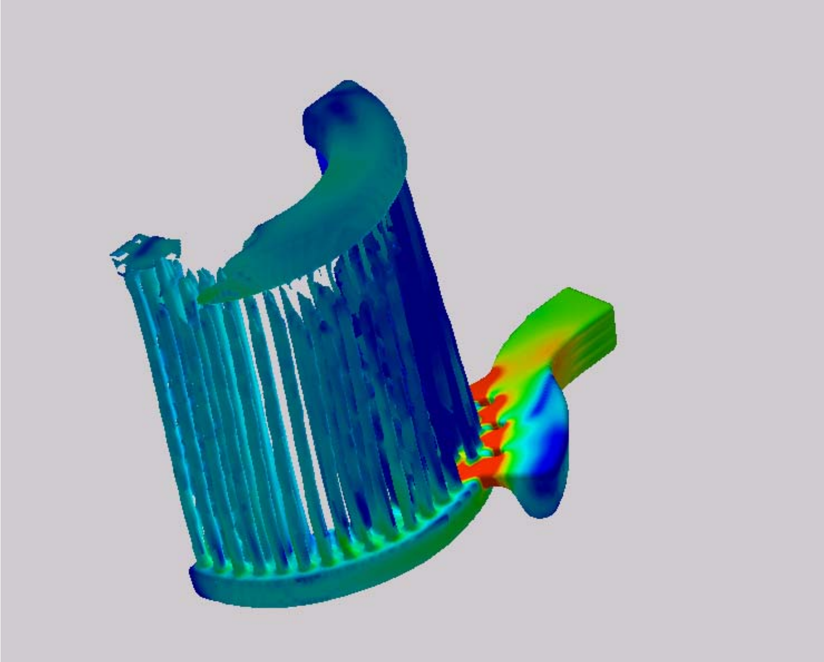


Figure 11 – Ejector End Ring in the 20% Pre-fill Simulation.

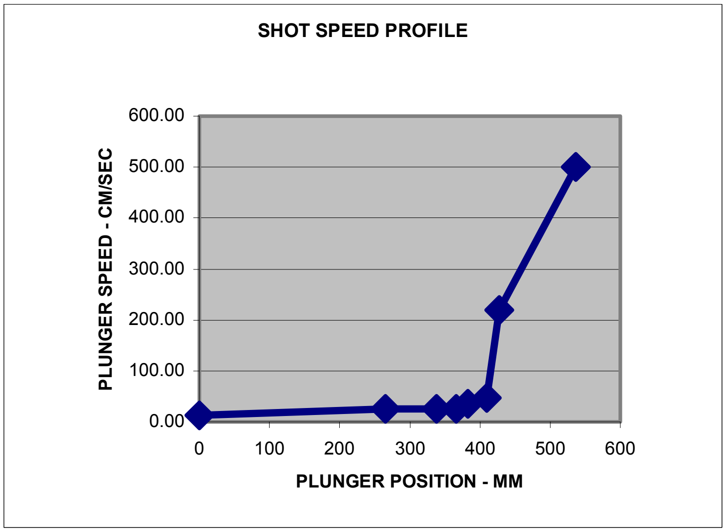


Figure 12 – Shot Speed Profile Used in Simulation of 20% Pre-fill with Slower Acceleration to the Fast Shot Speed.

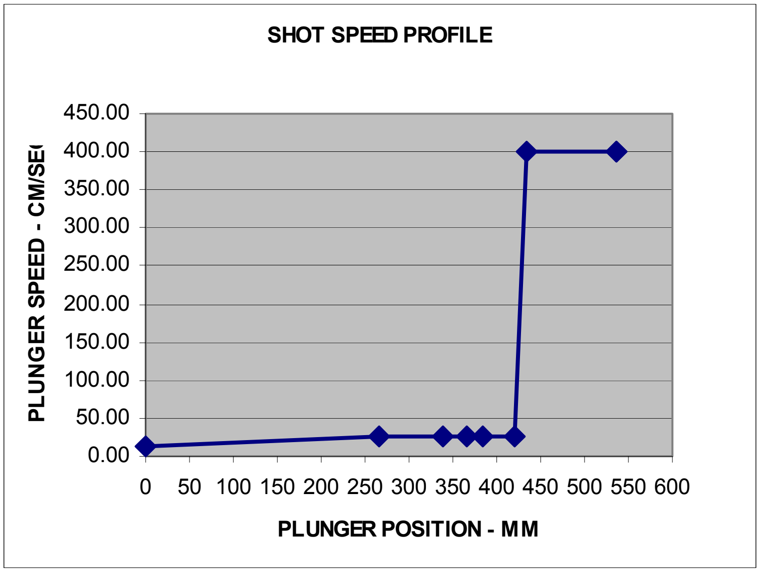


Figure 13 – Shot Speed Profile Used in the 40% Pre-fill with Delayed Acceleration to the Fast Shot Speed.

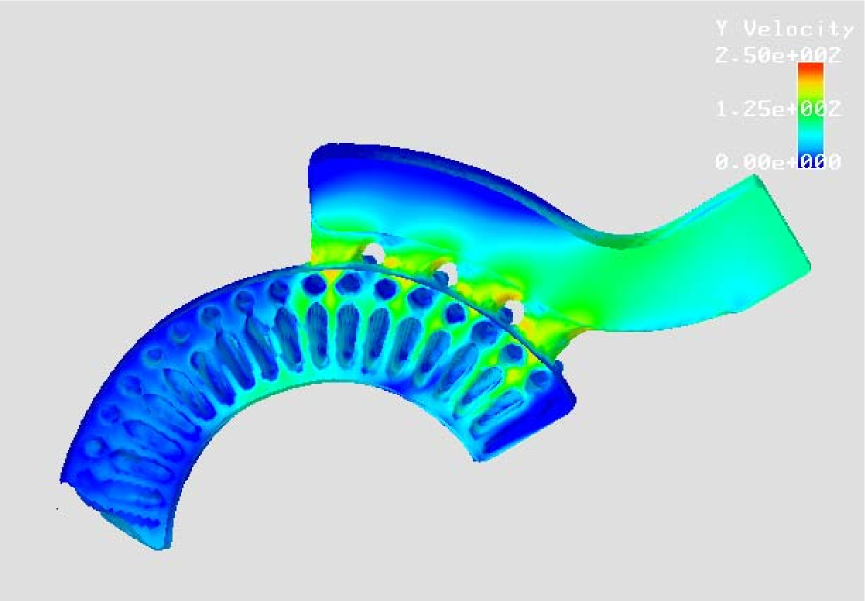
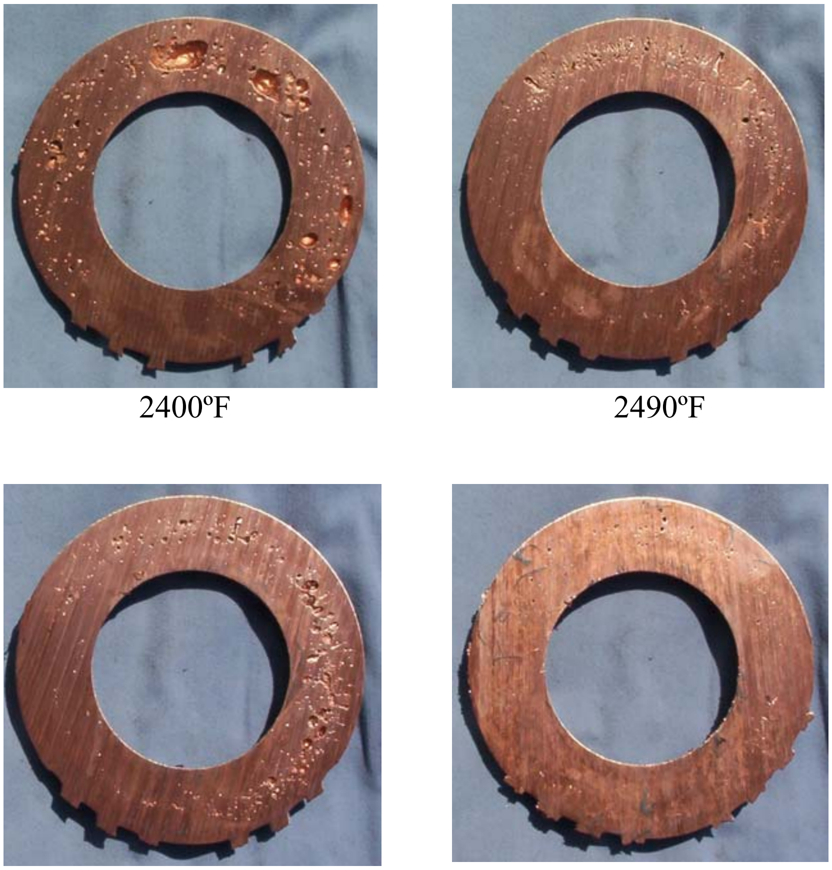


Figure 14 – Gate End Ring Simulation of 40% Pre-fill with Delayed Transition to Fast Shot Speed.
Bubble that was starting to form in an earlier frame has disappeared and the end ring has no large pores.



2400ºF

2490ºF

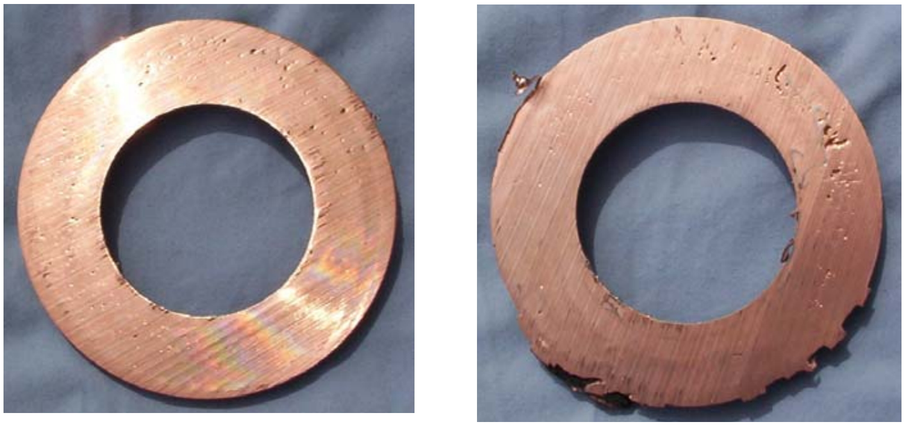
2580ºF

2670ºF

Figure 15 – Photographs of Sectioned Gate End Rings for Shots Made at Four Melt Temperatures.

Speed Transition in Runner

33% Pre-fill



55% Pre-fill

Figure 16 – Photographs of Sectioned End Rings with Increasing Pre-fill. Ejector end rings on left; gate end rings on right.

Tables

Table 1 – Shot Profile Transitions for Baseline Case Simulation

Travel Dist. (cm)	**Speed (cm/sec)**	**Percent Full**
0.00	13.00	Start
26.56	50.00	Sleeve full
33.76	50.00	Metal into model
36.60	130.00	Metal at gate
38.31	280.00	10% pre-fill point
42.00	280.00	32% mid travel point
51.50	280.00	87% mid travel point
53.70	100.00	Part full
53.70	100.00	Allowance for overflows

Table 2 – Shot Profile Transitions for 20% Pre-fill Simulation

Travel Dist. (cm)	**Speed (cm/sec)**	**Percent Full**
0.00	25.00	Start
26.56	25.00	Sleeve full
33.76	25.00	Metal into model
36.60	25.00	Metal at gate
40.02	450.00	20% pre-fill point
45.00	450.00	49% mid travel point
49.00	450.00	73% mid travel point
53.70	450.00	Part full
53.70	450.00	Allowance for overflows

Table 3 – Shot Profile Transitions for Simulation of 20%
Pre-fill with Slower Acceleration

Travel Dist. (cm)	**Speed (cm/sec)**	**Percent Full**
0.00	13.00	Start
26.56	25.00	Sleeve full
33.76	25.00	Metal into model
36.60	25.00	Metal at gate
38.31	36.00	10% pre-fill point
41.00	47.00	26% mid travel point
42.70	220.00	36% mid travel point
53.70	500.00	Part full
53.70	500.00	Allowance for overflows

Table 4 – Shot Profile Transitions for Simulation of 40% Pre-fill with Delayed Transition to Fast Shot Speed

Travel Dist. (cm)	**Speed (cm/sec)**	**Percent Full**
0.00	13.00	Start
26.56	25.00	Sleeve full
33.76	25.00	Metal into model
36.60	25.00	Metal at gate
38.31	25.00	10% pre-fill point
42.00	25.00	32% mid travel point
43.50	400.00	40% mid travel point
53.70	400.00	Part full
53.70	400.00	Allowance for overflows