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TILT POUR TRIALS AND ANALYSIS

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Abstract

The use of tilting molds in steel casting to reduce inclusion severity is investigated through a series of plate casting trials. In the tilting molds used for these casting trials, metal is initially poured into a holding basin in the mold and held for several seconds, in order to allow reoxidation inclusions that form during pouring to grow and float to the top of the basin. Then the entire mold is tilted to transfer metal from the holding basin into the casting cavity. Filling a casting cavity through tilting rather than by using standard pouring and gating techniques transfers the metal with less turbulence and splashing, thus reducing air entrainment. By reducing air entrainment, less oxygen is brought into contact with the metal, and hence fewer reoxidation inclusions form. Since reoxidation inclusions constitute a significant portion of the total inclusion population, this significantly reduces the overall severity of inclusions in the casting. In the casting trials described here, plates were cast with tilting molds as well as with standard molds using typical gating, for comparison. The cope surfaces of all plates were machined and the inclusions were counted. It is found that the tilting mold technique used in this work can substantially reduce inclusion severity, compared to standard techniques.

Introduction

The removal of oxide inclusions from castings and the subsequent repair of those castings are expensive and time consuming procedures. Svoboda et al. [1] estimated that twenty percent of the cost of producing castings is due to the removal of inclusions and the repair of the resulting defect areas with weld metal. Inclusions that remain in the casting adversely affect machining and mechanical performance, and may cause the casting to be rejected for failing to meet the radiographic standard requirements specified by the customer regarding allowable inclusion severity. In light of this, it is in the best interest of the steel casting industry to pursue the development of casting methods capable of reducing the quantity of oxide inclusions in castings.

Reoxidation inclusions, which form when deoxidized steel comes into contact with oxygen during mold filling, make up a substantial portion of the inclusions found in steel castings. Griffin and Bates [2] estimated that 83% of the macro-inclusions found in low-alloy steel castings are reoxidation inclusions, as are 48% of those found in high-alloy steel castings. The primary source of oxygen in reoxidation inclusion formation is air, which contacts the metal stream during pouring and the metal free surface in the mold cavity during filling. Since contact between the metal and air during filling is the primary source of reoxidation inclusions, several techniques have been developed to minimize this contact. Two examples of this are the use of thin, flat runners and tapered downsprues. Thin, flat runners provide minimal surface area between metal and air, and tapered downsprues entrain less air because they quickly fill (and stay full) during pouring.

Another idea that has not been widely implemented is that of pouring the metal into a reservoir located in the mold, and then tilting the mold to transfer the metal from the reservoir into the casting cavity. This idea was first proposed in 1916 by Durville [3], for the production of ingots. His idea further stated that the pouring-out surface of the reservoir and the pouring-in surface of the casting should lie along a straight line. That way, when tilting is performed, the metal free surface remains horizontal as metal is transferred smoothly from the reservoir into the casting cavity (see Figure 1). Transferring metal in this manner eliminates the excessive turbulence and splashing that occur during pouring, both of which lead to air entrainment and the mixing of oxide inclusions into the melt.

Several other people have since filed patents using similar mold tilting techniques. Seaton and Seaton [4] patented an assembly-line procedure for Ford Motor Company in which a nozzle is connected to the bottom of a mold cavity to fill it with metal (thus gaining the advantages of a smooth, quiescent bottom fill); once filling is complete, the mold is rotated 180° and allowed to solidify. The benefit to this procedure is that, once the mold is rotated, the filling nozzle is on top of the mold. It can then be disconnected and re-connected to the next mold in the line, without having to wait for the first casting to solidify. Kahn and Kahn [5] patented a procedure in which they also bottom-fill a mold, rotate it 180° and allow it to solidify. However, they add two new elements: (1) to prevent oxidation, they use a sealed system with a "protective gas" (most likely an inert gas such as argon) to prevent contact with oxygen, and (2) once the mold is rotated, they pressurize the system, to improve the casting soundness. An additional benefit to

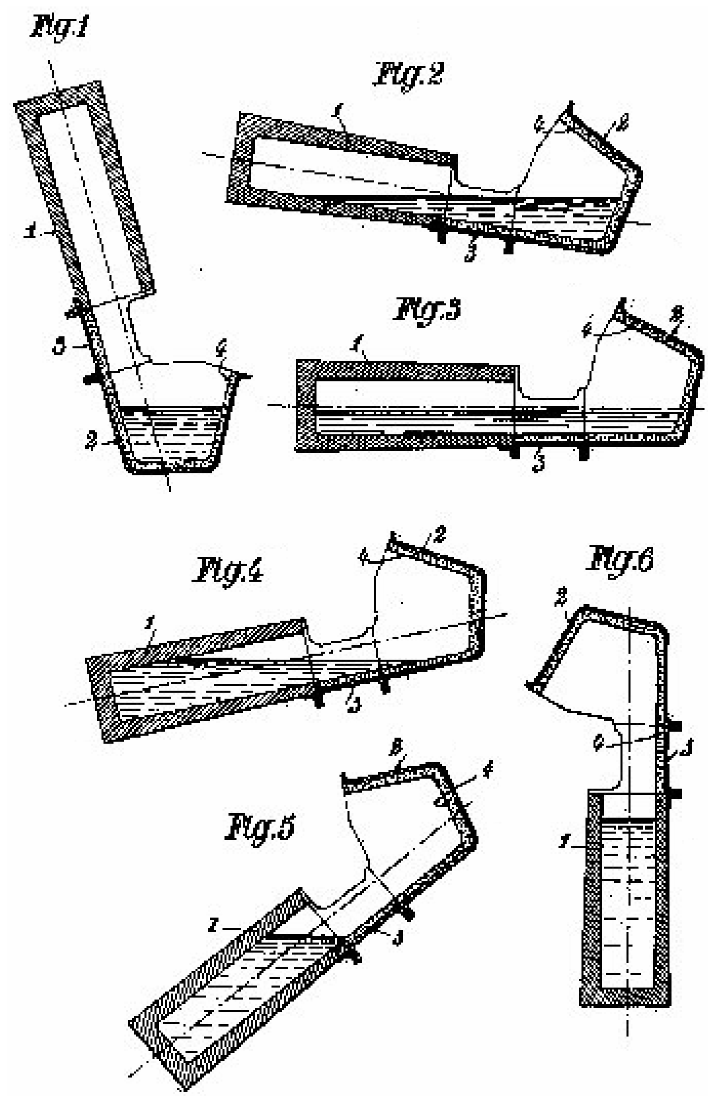


Figure 1 Figures illustrating the mold tilting process. The progression of mold tilting is shown in Fig. 1 – Fig. 6. Reproduced from Durville [3].

these mold tilting ideas is that the need for gating can be drastically reduced or even eliminated; the designs by Seaton and Seaton [4] and Kahn and Kahn [5] allow the metal to flow into the casting cavity through the risers. Reduction or elimination of gating will improve casting yield.

Although several researchers have investigated the idea of mold tilting, no literature was found that quantified the difference that this technique makes with regard to oxide inclusions. In addition, while the idea of mold tilting has been applied in industry for large-scale aluminum castings, it has not been utilized in the steel casting industry on a scale smaller than ingots. The purpose of this study is to determine if mold tilting is a worthwhile technique for production castings in the steel casting industry. This is accomplished by developing a mold tilting system, producing castings with both the new mold tilting system and using a standard gating system, and then comparing the resulting castings to determine to what degree a mold tilting system can reduce oxide inclusion formation. It should be noted that this project is ongoing, and therefore this paper is not a final report on mold tilting; it is only intended to describe the casting trials and to summarize the preliminary findings.

Tilting Mold Development

The preliminary design concept for the mold tilting trials uses the basic idea of the Durville process [3], with several variations made for practical reasons. The mold was developed with a vertical parting line (see Figures 2(a) and 2(b)), and was designed to rotate 90° (rather than 180°) to deliver the metal from the receiving basin to the casting cavity, as shown in Figures 2(c) – 2(e). The receiving basin is lined with an exothermic sleeve and a piece of refractory board on the bottom, to insulate the metal and prevent it from freezing before it is delivered to the casting cavity. A wide, thin plate shape (1"T x 10"W x 12"L) was chosen for the casting, in order to provide a large, uniform cope surface on which inclusions could easily be counted. For the purposes of tilting, the mold was designed with a hole through it. The idea is to insert a bar through the hole, and connect this bar to a tilting mechanism similar to that used to tilt pouring ladles.

In order to optimize the mold design before it was constructed, simulation was utilized. The Rotacast module of MAGMAsoft [6], which can simulate mold tilting, was used to predict the flow of metal from the holding basin into the casting cavity. Simulations were run using 1025 steel and no-bake (furan) sand with a variety of different mold designs and tilting times, and the geometry/tilting time combination that produced the lowest metal velocities throughout the tilting process was selected. A tilting time of six seconds was selected, with the geometry shown in Figure 3. This design includes an additional refractory plate (see Figures 3(a), 3(c) and 3(d)), which was added to create a t-pot basin, to prevent any slag that forms on the surface of the holding basin from entering the casting cavity during tilting. Velocity contours for this geometry at several times during tilting are shown in Figure 4. Note that, even though tilting only takes six seconds, it takes eight seconds for the metal to flow to its final position. With this design, the maximum velocity is less than 50 cm/s for most of the tilting process, reaching as high as about 70 cm/s from 5.5 – 6.0 seconds after the start of tilting. If tilting is not used, the maximum velocity during pouring is around 165 cm/s. Thus, a significant reduction in velocity (and turbulence and splashing) results from this tilting design.

Casting Trials

All of the casting trials discussed in this paper were performed at Matrix Metals Keokuk Facility (Keokuk Steel Castings). Chemical analysis was performed on a ladle sample from each heat used, and further chemical analyses were performed on metal samples from the holding basin and the resulting plate for each tilt mold plate produced. The cope surface of all plates (standard and tilt plates) was machined, removing 1/8 inch. After machining, inclusions were counted and the plates were radiographed and rated according to ASTM standards.

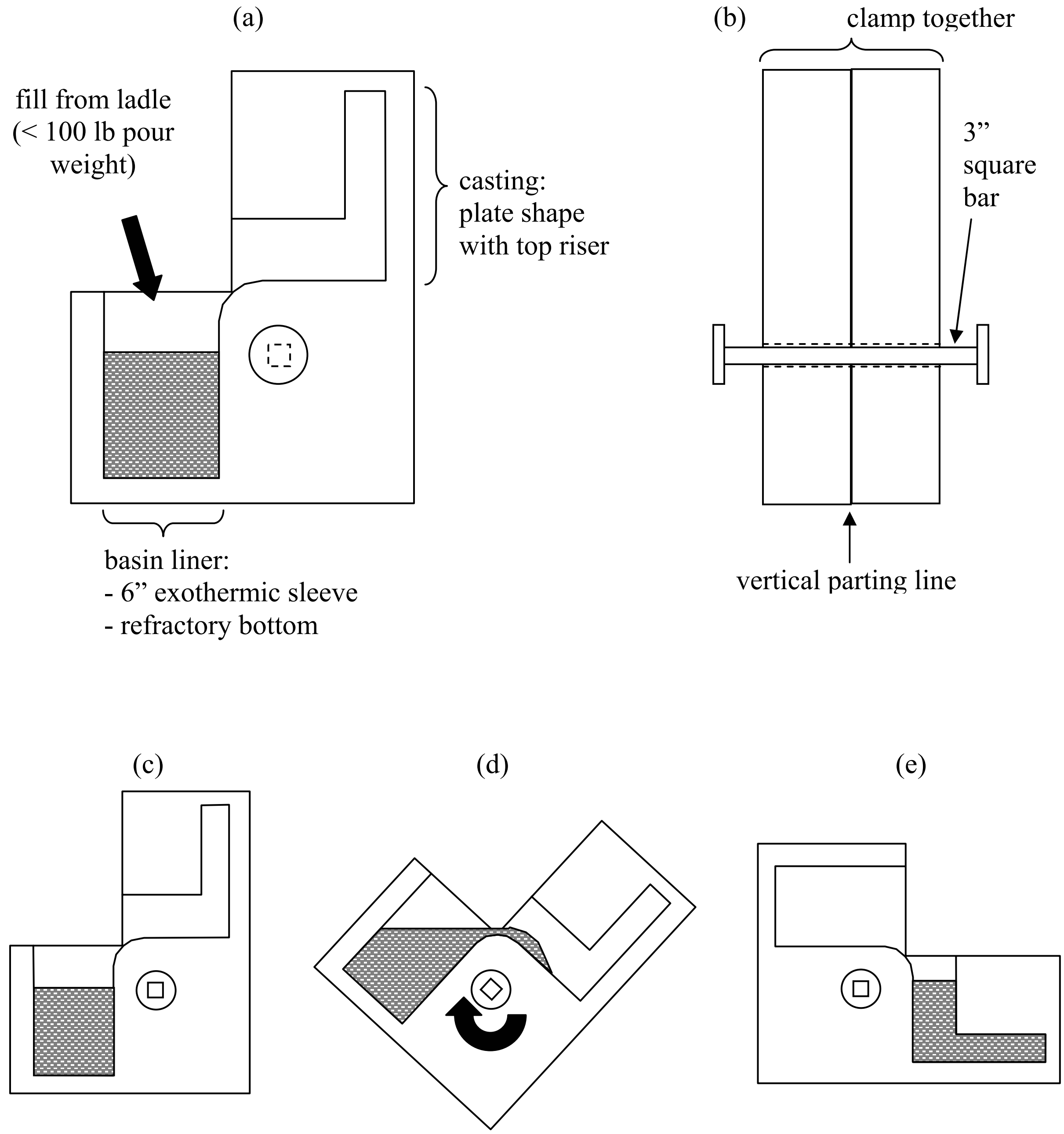


Figure 2 Sketches of the initial concept of the mold tilting trials. (a) and (b) show two views of the mold, and (c) – (e) illustrate the tilting process.

Before beginning the casting trials, a couple of tests were performed to investigate tilting options and determine if the original concept would be able to produce the desired castings. Pictures of a test mold created to study tilting options are shown in Figure 5. Figure 5(a) shows the entire mold in the upright position necessary for basin filling, and Figure 5(b) shows half of the mold, so the inside can be seen. The exothermic sleeve was not used in this test mold, since it was not meant to be used for casting. Figure 5(b) also shows the location of a test coupon that was added for the casting trials, to allow chemical analysis of the metal in the basin. For illustrative purposes, Figure 6 shows four views of a casting that was produced in a test of the tilting procedure, prior to the first casting trials. This figure shows the thin shell of metal that remains around the pouring basin, as well as the channel through which the metal flows to travel from the basin into the plate cavity. The location of the insulating sleeve can be clearly seen in Figure 6(a). With respect to inclusions, the as-cast surface of the plate looks very clean.

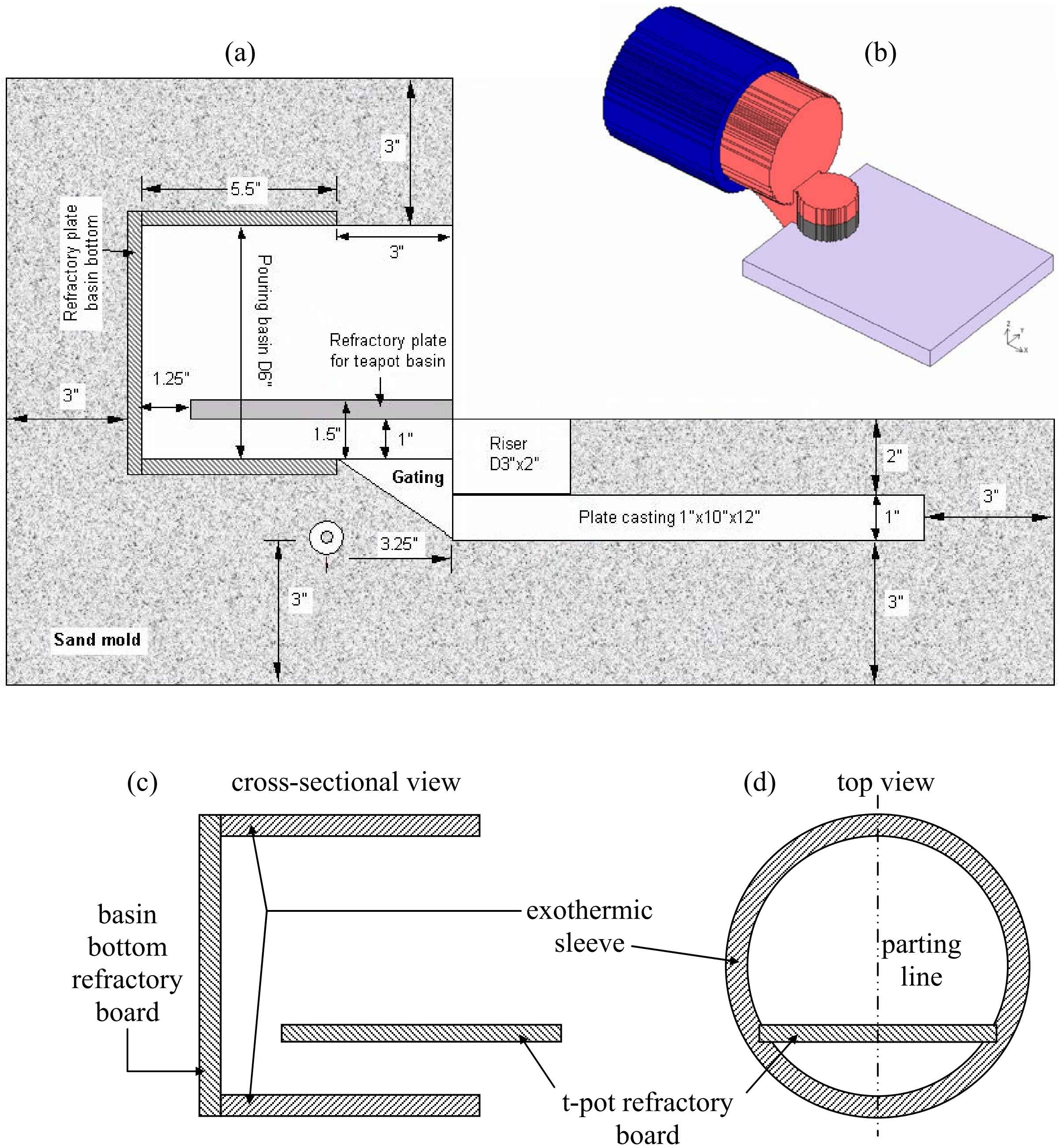


Figure 3 Design selected for the mold tilting trials: (a) cross-sectional view of the mold; (b) isometric view of the pouring basin (with exothermic sleeve) and plate; (c) cross-sectional and (d) top views of the t-pot basin.

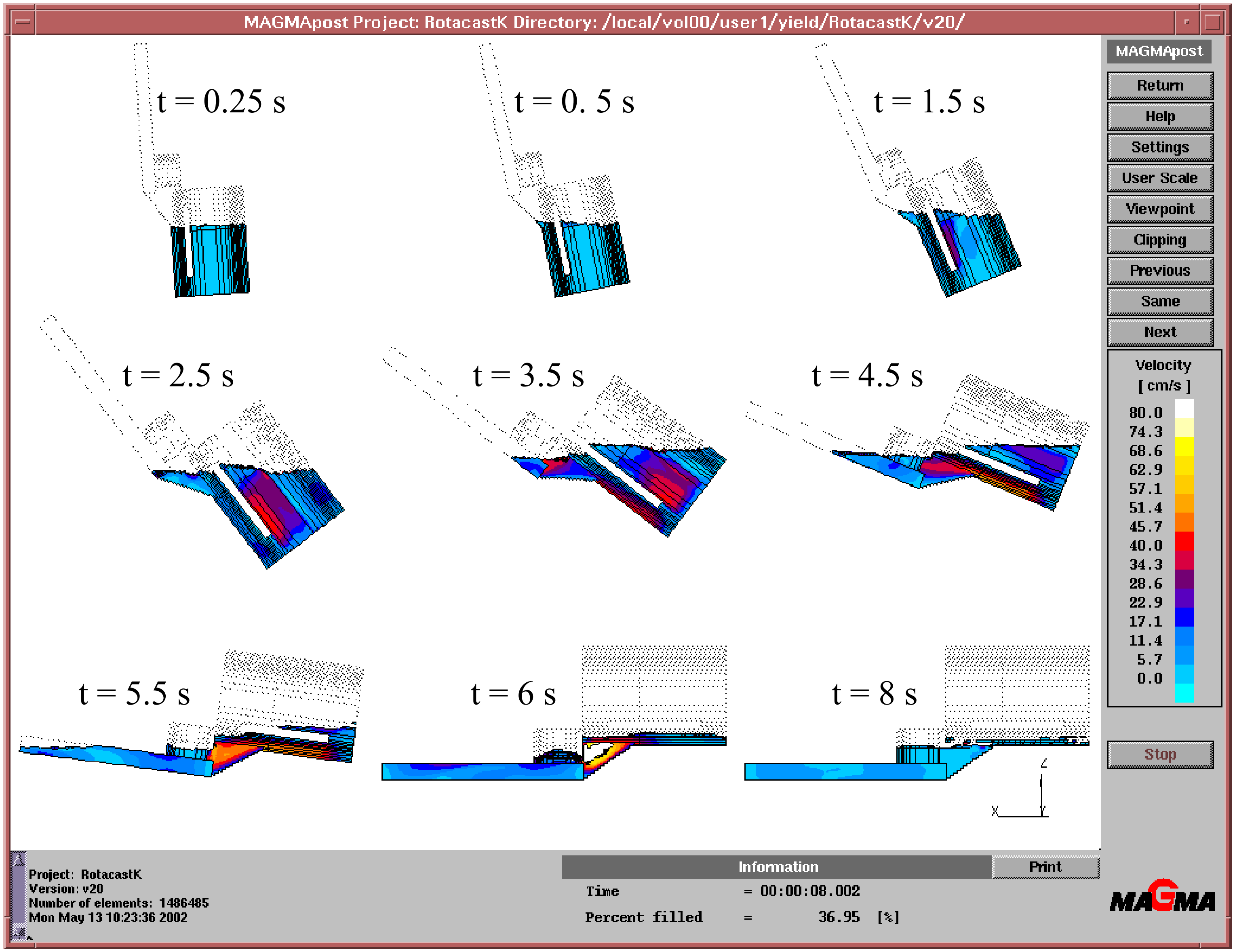


Figure 4 Velocity contours at several times during a simulation with a tilt time of 6 seconds.

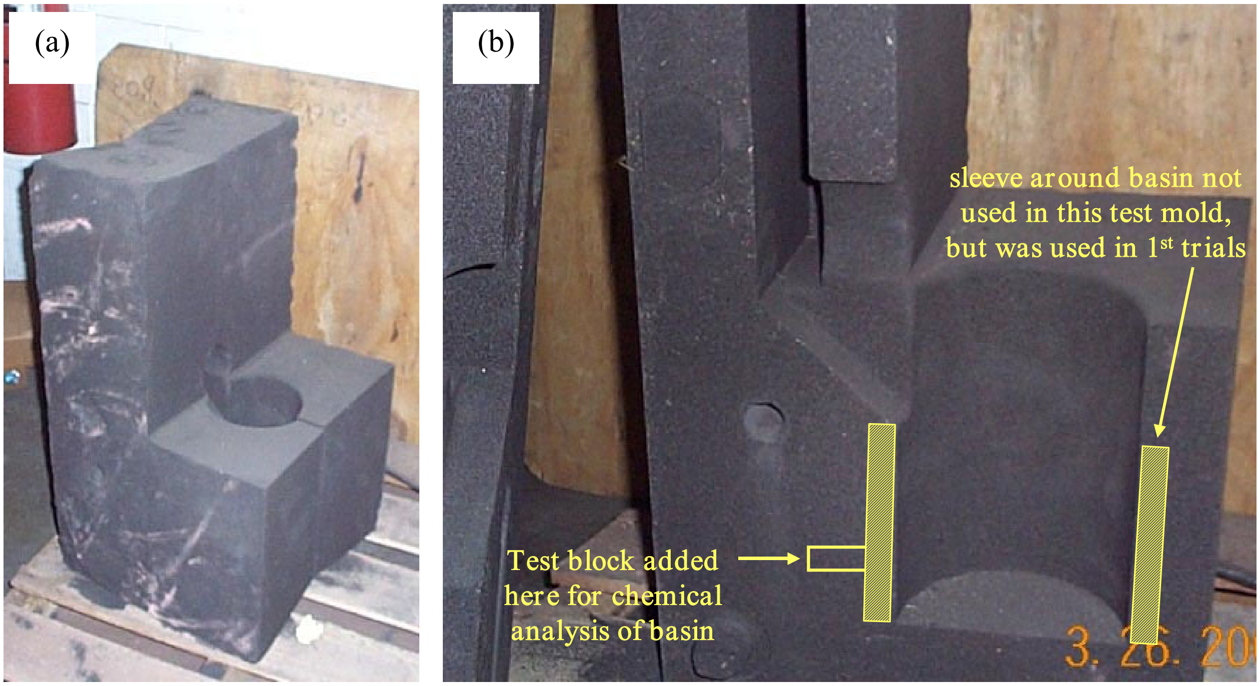


Figure 5 Pictures of (a) complete mold and (b) half mold; this mold was created to test tilting options.

First Trials

For the first casting trials, performed in March 2003, three plates were cast with the tilting procedure, and three plates were cast using a standard mold, with typical gating for such a casting (see Figure 7). In this set of trials, the refractory boards shown in Figure 3 (one to create a t-pot basin and one to insulate the bottom of the holding basin) were not used; in other words, all three tilt molds had a lip pour holding basin in the first trials. All plates (standard and tilt) were poured from the same ladle of the same heat. The alloy used in this set of trials was 1019 steel, which was poured at 2878°F. It should be noted that all molds for all the trials performed were made with no-bake sand.

Figure 8 shows the tilt molds prior to pouring. After consideration of different methods of tilting, it was decided to use a very simple manual procedure for tilting in these proof-of-concept trials, and to worry about developing a more sophisticated method once it had been demonstrated that the process was a worthwhile method of casting. To that end, long boards were clamped onto either side of the tilting molds; after the holding basin in the mold was filled, a foundryman used the boards to manually lower the mold from the upright position shown in Figure 8 to the horizontal position shown in Figure 9.

Table 1 gives a summary of the important features of the first casting trials. Note that the pouring time was not measured for the tilt molds. The tilting times were all between seven and eight seconds. All six plates had significant ASTM x-ray shrinkage levels—this was not surprising, since the feeding length for the plate geometry exceeded the feeding distance of the riser; the focus was more on creating a large cope surface than on producing sound plates. In

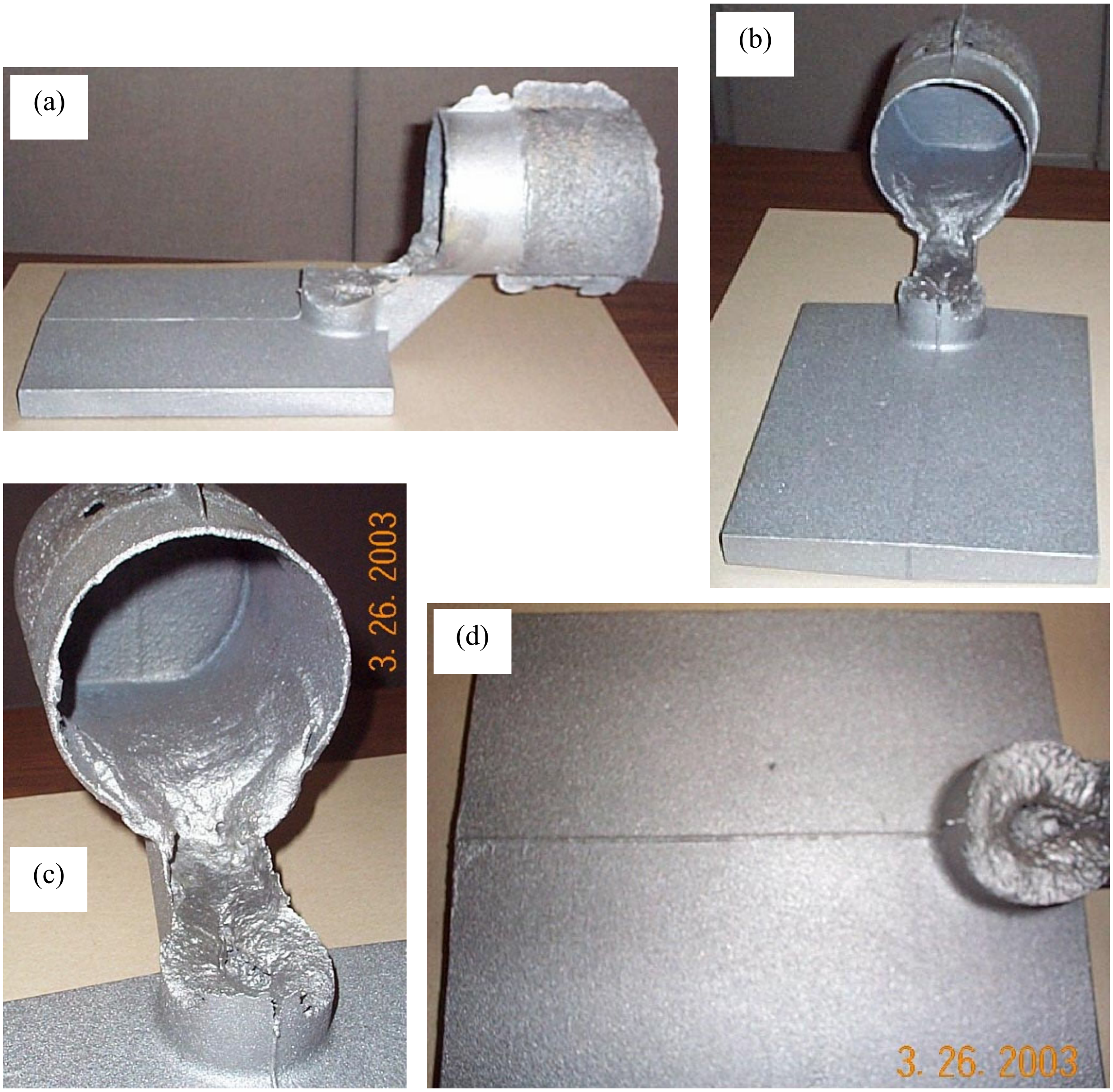


Figure 6 Four views of a test tilt casting.

addition to significant x-ray shrinkage indications, two of the three standard plates also had x-ray inclusion indications (B1 and B2); none of the tilt plates had inclusion indications. Examining the inclusion counts, however, there is no significant difference between the tilt plates and the standard plates. The inclusion counts shown in Table 1 were obtained by drawing one-inch circles around groups of inclusions on the machined surface of each plate, until all visible inclusions were encompassed within a circle. The number of circles is then taken as the inclusion count. Examples of inclusion counts are shown in Figure 10(a) for a standard plate, and in Figure 10(b) for a tilt plate.

Table 1 Summary of results from the first casting trials.

1st Trials	- 1019 steel, T_{pour} = 2878°F - all plates poured from same heat, same ladle					
Plate	Pour Time (s)	Tilt Time (s)	Inclusion Count	ASTM X-ray Shrinkage Rating	ASTM X-ray Inclusion Rating	ASTM X-ray Porosity Rating
Tilt #1		8	6	CD4	-	A1
Tilt #2		7	7	CD4	-	A1
Tilt #3		8	7	CD5	-	-
Standard #1	8	n/a	5	CA2	B1	-
Standard #2	7	n/a	5	CA3	B2	A1
Standard #3	7	n/a	8	CA3	-	-

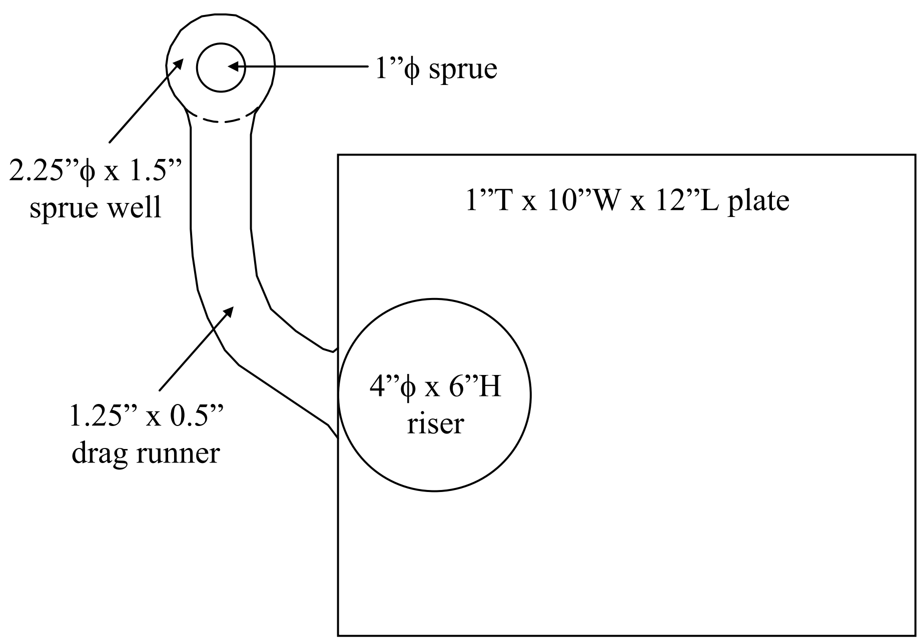


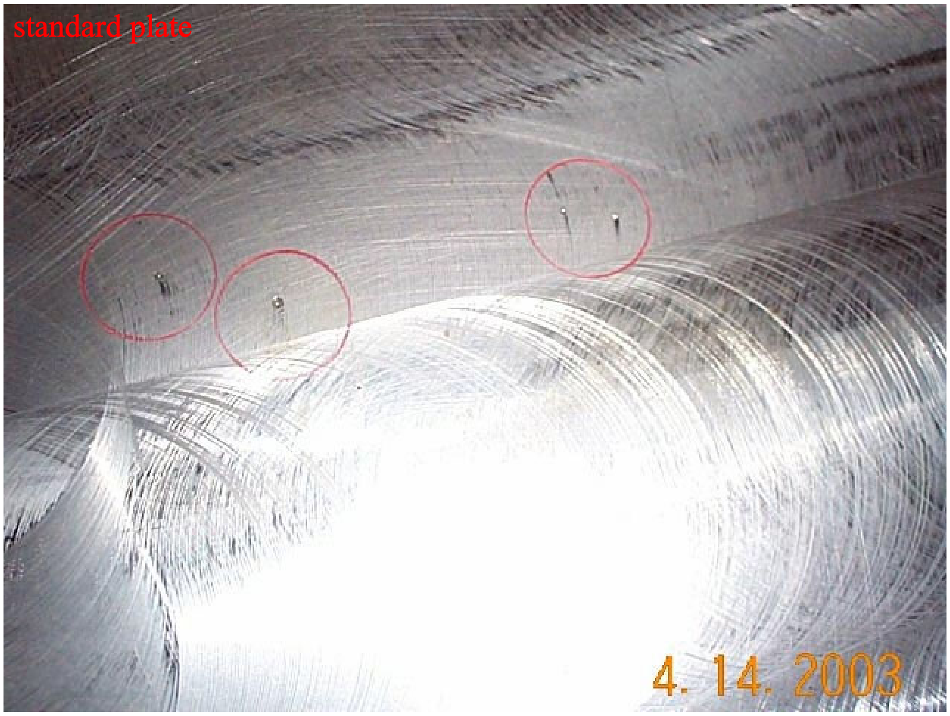
Figure 7 Gating diagram for standard mold plates.

One possible explanation for the lack of reduction in the inclusion counts between the tilt and standard plates is that perhaps the inclusions that were counted in the tilt plates, such as those seen in Figure 10(b), were actually not inclusions, but rather part of the extensive shrinkage that occurred in the casting (all the tilt plates had ASTM shrinkage levels CD4 or CD5). This idea is supported by the fact that no inclusions were seen on the radiographs. In any case, the tilt casting process was analyzed after little difference was seen in the inclusion counts between the tilt and standard plates. It was determined that a potentially important step was missing from the process. For each tilt mold, after the holding basin was filled, the mold was immediately tilted. This did not allow time for inclusions formed during the filling of the holding basin to grow and float to the top of the basin, forming a small slag layer there. Thus, any inclusions created during

Figure 8 Tilting molds ready for pouring during first trials.

Figure 9 A tilting mold after pouring and tilting.

(a)



(b)

Figure 10 Examples of machined plate surfaces from first casting trials for (a) a standard plate and (b) a tilt plate, showing 1" inclusion count circles.

the filling of the holding basin were still in the melt, and were swept into the casting when it was tilted. It was decided that, in the next set of trials, a holding time would be introduced after pouring and before tilting, in order to allow inclusions time to float to the surface of the melt.

Finally, Table 2 summarizes the chemical analysis for the first tilt plate. Samples of metal were taken from the ladle, from the holding basin (using the test coupon shown in Figure 5) and from the plate. Note the increase in nitrogen and oxygen between the ladle and the basin; this shows the increase of gases taken from the air during pouring. The oxygen level then drops considerably between the basin and the plate, likely due to the formation of oxides.

Table 2 Chemical analysis for Tilt Plate #1.

Test Bar from…	Element (wt %)						
	C	Mn	Si	Ni	Cr	Mo	Al
Ladle	0.199	1.06	0.53	0.09	0.16	0.08	0.0435
Basin	0.192	1.06	0.53	0.08	0.15	0.08	0.0467
Plate	0.195	1.07	0.54	0.08	0.15	0.08	0.0453

Test Bar from…	Element (wt %)					
	P	S	Fe	Cu	N	O
Ladle	0.019	0.026	97.61	0.121	0.0079	n/a
Basin	0.019	0.029	97.61	0.122	0.0107	0.0225
Plate	0.020	0.027	97.60	0.118	0.0103	0.0122

Second Trials

For the second tilting trials, performed in May 2003, the holding time mentioned above was added for the tilt plates, to allow inclusions to float out of the holding basin after pouring. A holding time of fifteen seconds was planned for all three tilt plates. In addition, the three tilt plates had slight variations in their mold arrangements: the mold for tilt plate #1 used a refractory board to insulate the bottom of the holding basin, but did not use one to create a t-pot basin (i.e., it was a lip pour basin, as in the first trials); the mold for tilt plate #2 used refractory boards both to insulate the bottom and to create a t-pot basin; the mold for tilt plate #3 did not use a refractory board to insulate the bottom of the basin, but did use one to create a t-pot basin. As in the first trials, three plates were also cast using a standard mold and gating, for comparison. All plates were again poured from the same ladle of the same heat. The alloy used in this set of trials was 4318 steel, which was poured at 2836°F. It is worth noting that this turned out to be a dirty heat; this will be discussed later.

The second tilting trials are summarized in Table 3. The pour/tilt time column of the table indicates pouring time for standard plates and tilting time for tilt plates. The tilting time for all tilt molds was about six seconds. The planned holding time of fifteen seconds was achieved for the first two tilt plates, but because the second and third plates were poured in rapid succession, the foundryman tilting the plates did not finish tilting the second plate until the third plate had been held for nineteen seconds. Note that the inclusion counts for the standard plates are much higher than in the first trials (see Table 1), because this was a dirty heat. An example of the severity of the inclusions in the standard plates can be seen in Figure 11, which shows the machined surface of standard plate #1. A key result in Table 3 is that the inclusion count for tilt plate #1 is significantly smaller than for any of the standard plates. This indicates that the tilt pour method does show promise in reducing inclusions. Both the as-cast and machined surfaces of tilt plate #1 are shown in Figure 12. Comparing Figures 11 and 12, it is evident that the tilt plate has a greatly reduced inclusion severity compared to the standard plate. A piece of slag is identified in the lower right portion of Figure 12(b). Even though this tilt plate, as well as all three tilt plates from the first trials, used a lip pour holding basin, the slag that formed in the basin was generally trapped in the gating rather than passing into the casting. The inclusion counts for tilt plate #1 and all three standard plates are shown in Figure 13. This figure clearly illustrates the improvement in the inclusion severity due to the tilting method. The radiographic and chemical analyses for the second trials have not yet been completed.

Table 3 Summary of results from the second casting trials.

2nd Trials	- 4318 steel, $T_{pour} = 2836°F$ - all plates poured from same heat, same ladle → dirty heat!					
Plate	Insulated Basin Bottom?	T-pot / Lip Pour Basin?	Pour/Tilt Time (s)	Holding Time (s)	Inclusion Count	Comments
Tilt #1	yes	lip pour	6	15	5	
Tilt #2	yes	t-pot	6	15	n/a	full of holes
Tilt #3	no	t-pot	6	19	n/a	full of holes
Standard #1	n/a	n/a	5	n/a	17	
Standard #2	n/a	n/a	5	n/a	13	
Standard #3	n/a	n/a	5	n/a	18	

Figure 11 Machined surface of standard plate #1 from second trials.

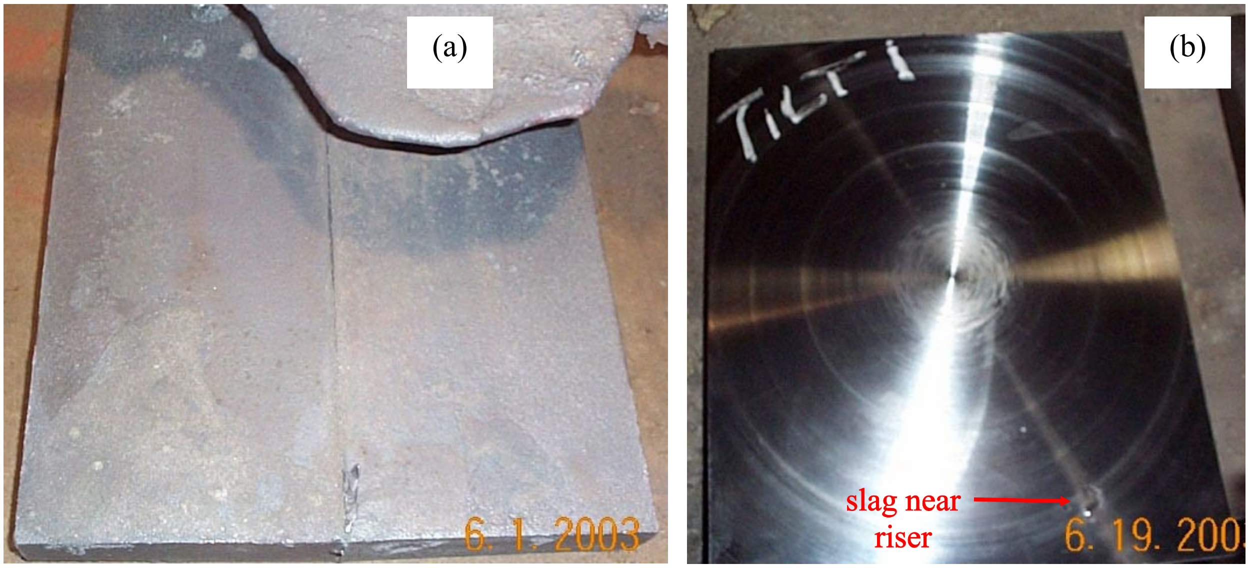


Figure 12   Tilt plate #1 from second trials: (a) as-cast surface; (b) machined surface.

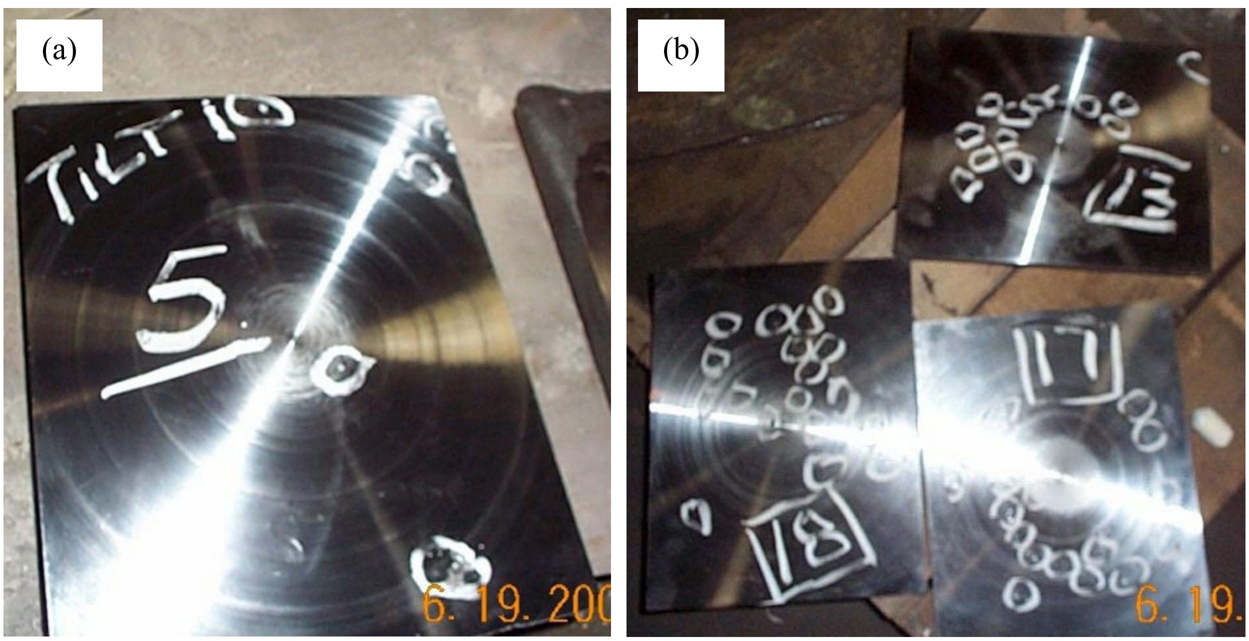


Figure 13   Machined plate surfaces for (a) tilt plate #1, and (b) all three standard plates, showing 1” inclusion count circles.

Unfortunately, the other two tilt plates (#2 and #3) turned out very poorly, due to an adverse chemical reaction between the metal and the refractory board that was used to create the t-pot basin. The bottom surface of each t-pot refractory board, around which the metal flowed when the mold was tilted, was cut to produce a board of the correct size; it was thought that the exposure of this uncoated surface of the refractory board to the metal is what produced the reaction. The resulting reaction produced a great deal of gas, which caused both of these plates to pour short, and gave their machined surfaces a swiss cheese-like appearance. The as-cast and machined surfaces of these plates are shown in Figures 14 and 15.

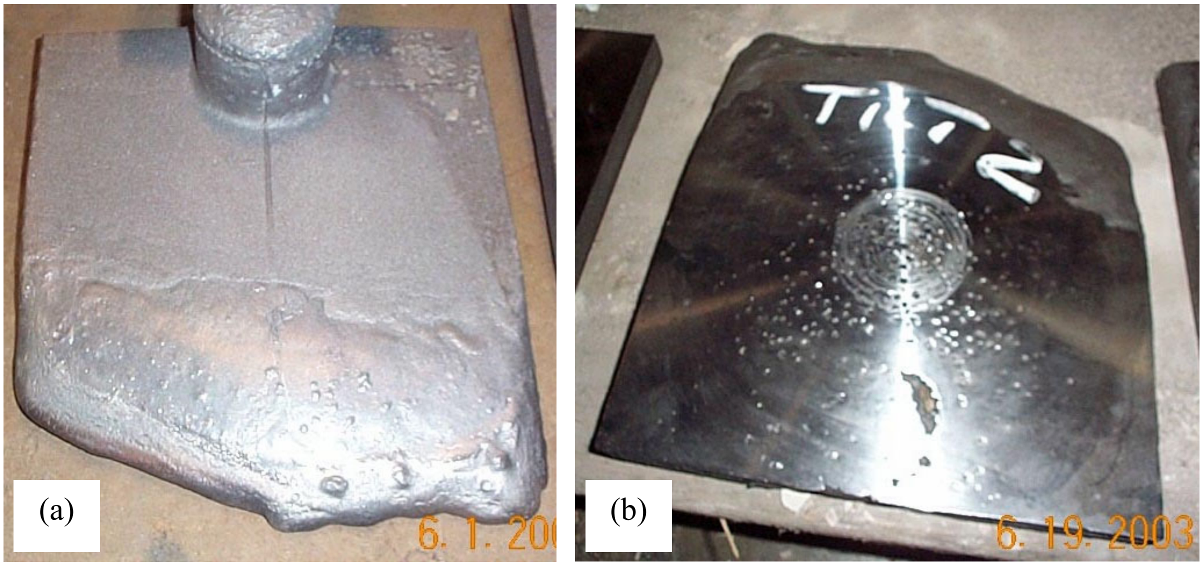


Figure 14 Tilt plate #2 from second trials: (a) as-cast surface; (b) machined surface.

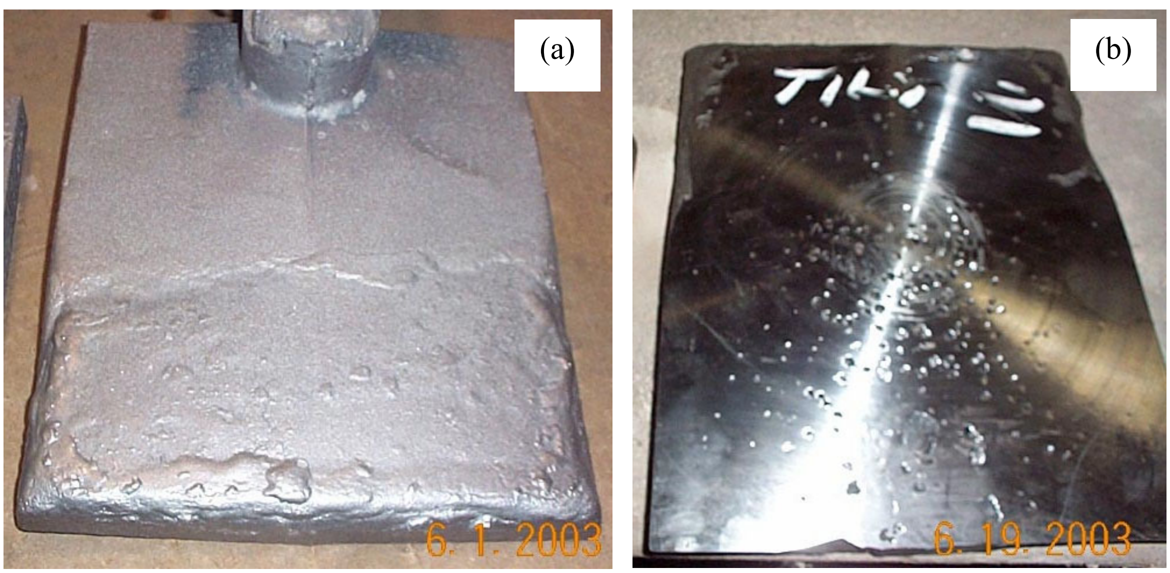


Figure 15 Tilt plate #3 from second trials: (a) as-cast surface; (b) machined surface.

<u>Third Trials</u>

The reaction between the metal and the t-pot boards in the second trials made it clear that another material would need to be used to create the t-pot basin. The new material selected was a section of a nine inch exothermic sleeve (see Figure 16). It was reasoned that the sleeve was coated, and that the metal in the holding basin was already in contact with an exothermic sleeve,

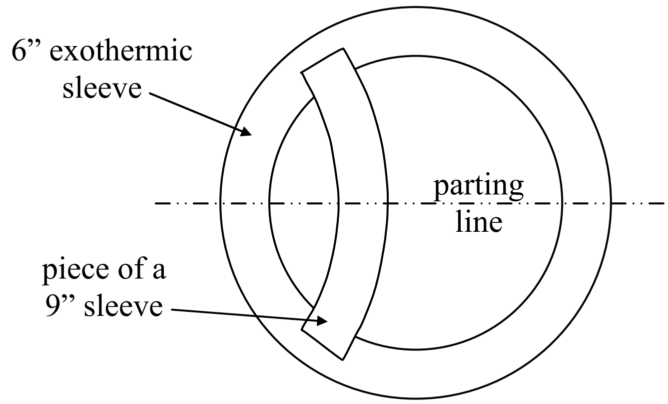


Figure 16 Top view of t-pot basin created using a section of a nine inch exothermic sleeve.

so this material should not create the same problems seen in the second trials. It was decided that the refractory board used to line the bottom of the holding basin was unnecessary, so the basin bottom refractory board was not used in these trials.

The third set of casting trials was performed in July 2003. There were three tilt plates for this set of trials: the mold for tilt plate #1 used a lip pour basin, and the molds for tilt plates #2 and #3 had t-pot basins. Only one standard plate was cast in these trials. All plates were again poured from the same ladle of the same heat. The alloy used in this set of trials was 1022 steel, which was poured at 2841°F. The original intent was to use a holding time of fifteen seconds for tilt plates #1 and #2, and ten seconds for #3. However, a difficulty that occurred during casting altered this plan somewhat. First of all, due to some re-arranging of the carts that held the tilting molds before pouring, the casting order was: tilt plate #3, tilt plate #2, tilt plate #1, standard plate. After tilt plate #3 was poured and held for ten seconds, and then tilted, there was difficulty keeping the mold on the cart. Because of this, it was jostled and moved around to slide it to a stable position on the cart, which took a few extra seconds. As a result, tilt plates #2 and #1 (which had already been poured) were subjected to holding times of twenty seconds each before they were tilted.

The results of the third trials are summarized in Table 4. Again, the pour/tilt time column records the pouring time for the standard plate, and tilting times for the tilt plates. The tilt time

Table 4 Summary of results from the third casting trials.

3rd Trials	- 1022 steel, T_{pour} = 2841°F - all plates poured from same heat, same ladle					
Plate	Insulated Basin Bottom?	T-pot / Lip Pour Basin?	Pour/Tilt Time (s)	Holding Time (s)	Inclusion Count	Comments
Tilt #1	no	lip pour	5	20	3	
Tilt #2	no	t-pot	5	20	n/a	full of holes
Tilt #3	no	t-pot	20	10	n/a	full of holes
Standard #1	n/a	n/a	5	n/a	5	

was about five seconds for tilt plates #1 and #2, and about twenty seconds for #3 (which can be broken into about eight seconds of tilting, and about twelve seconds of jostling and shifting to get the mold stable on the cart). The standard plate had an inclusion count of five, and tilt plate #1 had an inclusion count of three. Figures 17 and 18 show the as-cast and machined surfaces of the standard plate and tilt plate #1, respectively. Both machined surfaces (Figures 17(b) and 18(b)) look good.

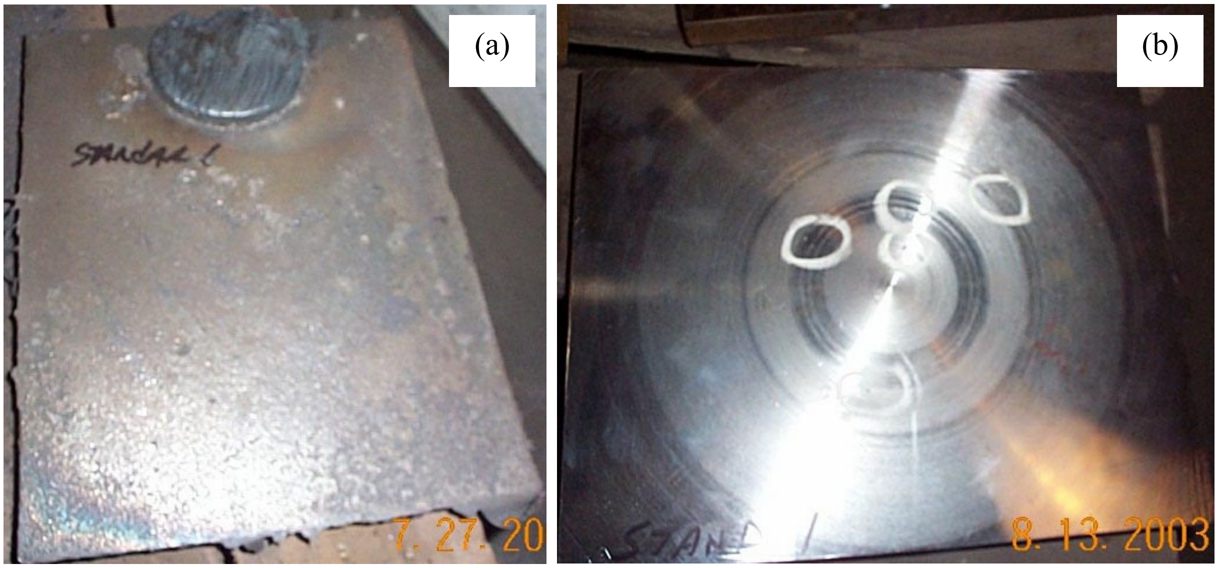


Figure 17 Standard plate from third trials: (a) as-cast surface; (b) machined surface.

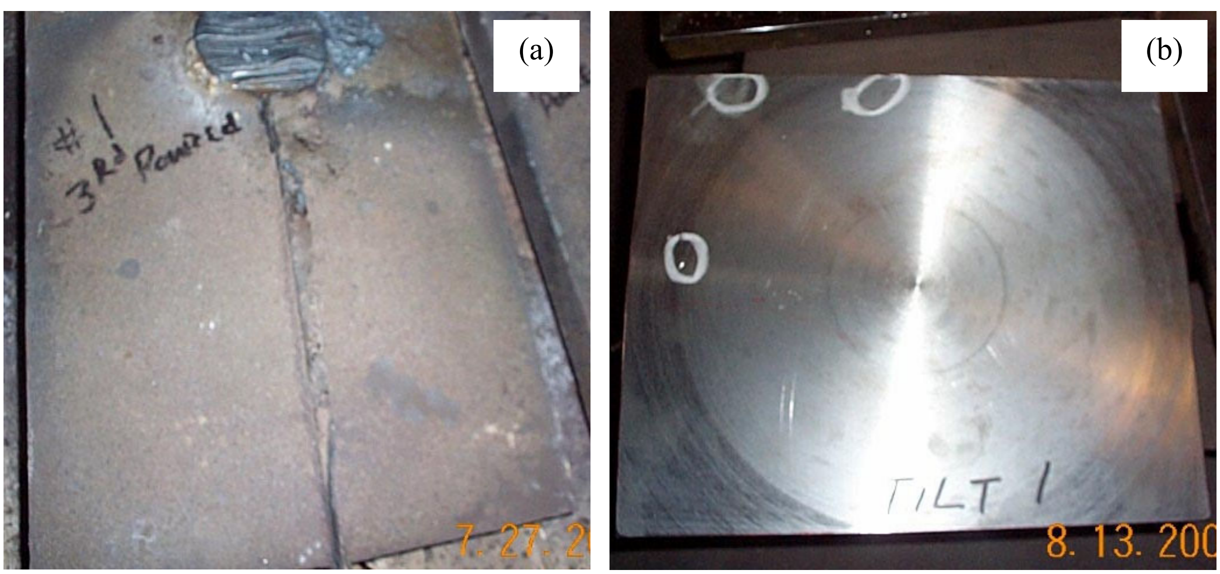


Figure 18 Tilt plate #1 from third trials: (a) as-cast surface; (b) machined surface.

Unexpectedly, tilt plates #2 and #3 again had an adverse reaction between the metal and the t-pot board. As seen in Figures 19(b) and 20(b), the strong reaction again created a great deal of gas, giving the machined surfaces a similar swiss cheese-like appearance (worse than in the second trials, in fact). It is interesting to note from Figures 19(a) and 20(a), though, that the as-cast surfaces of these plates look clean. The laplines visible in Figure 20(a) are the result of the difficulty encountered in lowering tilt mold #1 onto the cart; the shifting and jostling used to move the mold to a stable position on the cart created waves within the mold, which froze as the casting solidified.

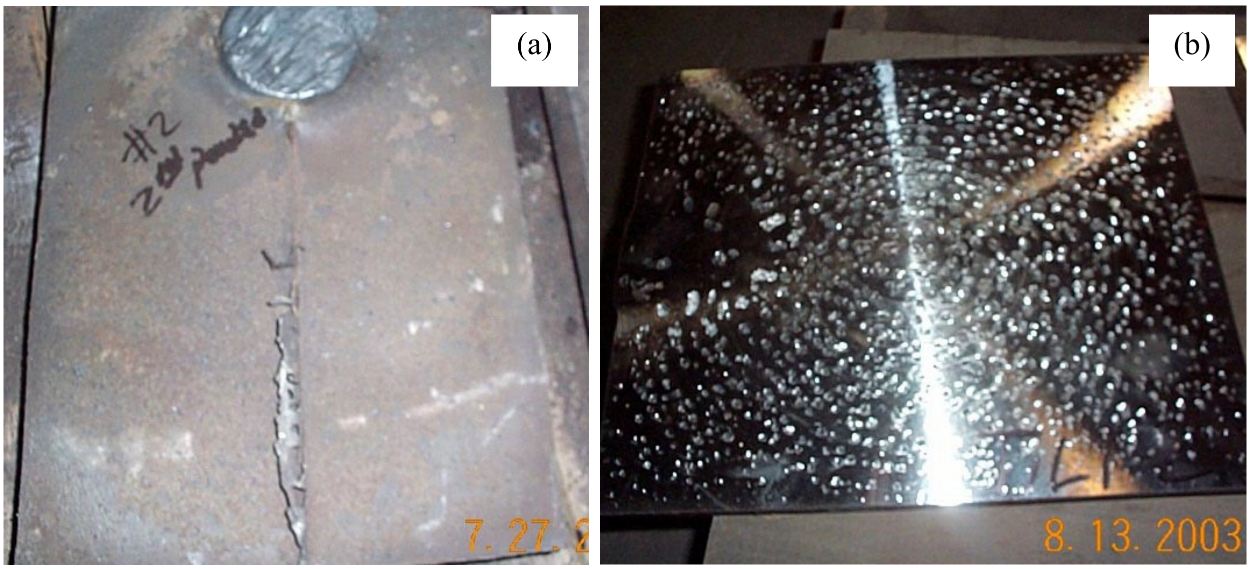


Figure 19 Tilt plate #2 from third trials: (a) as-cast surface; (b) machined surface.

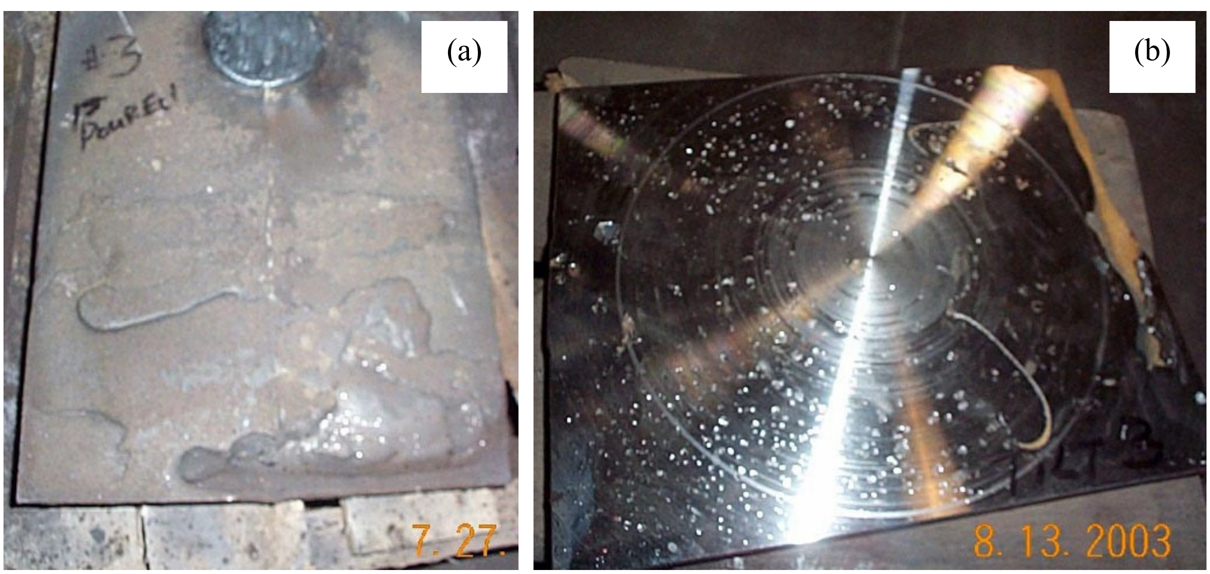


Figure 20 Tilt plate #3 from third trials: (a) as-cast surface; (b) machined surface.

It was decided in hindsight that more than one standard plate should have been cast. Because only one of the three tilt plates turned out to be useful, it is difficult to draw any meaningful conclusions from one tilt plate and one standard plate that have inclusion counts of three and five, respectively.

Conclusions

The tilting mold casting trials described in this paper indicate that filling a casting cavity with a tilting mold can indeed reduce the severity of reoxidation inclusion defects in steel castings. Particularly for the dirty heat used in the second casting trials, the plate produced by tilting had considerably fewer inclusion defects on the machined cope surface than did any of the three plates cast with a standard mold. It was found that a key element in the tilting process is to allow ten to twenty seconds of settling time after the tilt mold holding basin is filled from the ladle and before the mold is tilted, in order to allow reoxidation inclusions that form during pouring to float out of the melt before tilting is performed. Items of ongoing research include developing a t-pot basin that does not react with the melt, and developing a more automated tilting system. Once the process has been further refined, it will be applied to a production casting.

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