Watching Casting Defects Form

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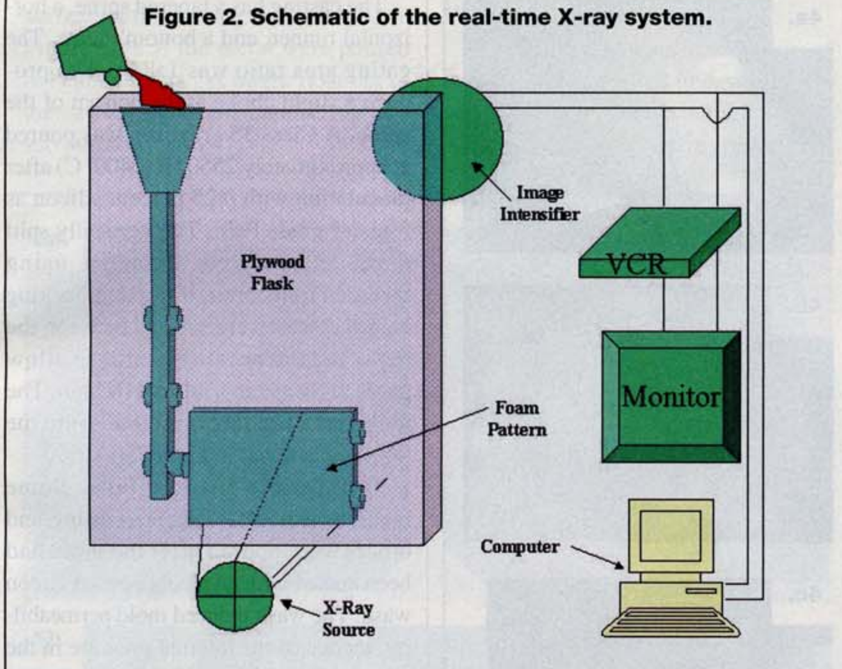
X-rays enable us to observe real-time mold filling in lost foam and conventional sand molds. These observations permit foundrymen to observe the reasons for casting defects as they are formed, rather than guessing at the causes after the casting cools. This capability is invaluable in producing quality castings and reducing scrap rates.

Dr. Charles Bates shows the real-time X-ray system. The X-ray source is on the right, and a mold, pouring apparatus, and X-ray detector are on the left side of the vault.

Foundries in the United States must become globally competitive in producing clean, quality castings. To accomplish this, the industry must become truly innovative to minimize lead time, improve casting quality, reduce scrap, and reduce the cost of operations. Developing consistent pouring and gating practices, and understanding and eliminating casting defects are important steps in accomplishing this goal and competing in the global marketplace. Understanding these factors will be beneficial in "making it right the first time" and eliminating a lot of time reiterating to find the best gate and riser sizes and locations.

Many casting defects originate during pouring and filling because of interactions between molten metal and air. As metal flows from the ladle through the pouring basin, sprue, runner, and into the mold, oxide films, air bubbles, and gas from cores can be entrained and degrade casting appearance and properties. The ability to watch metal flow into a mold is an aid to understanding and eliminating defect formation. The University of Alabama at Birmingham (UAB), with financial assistance from the U.S. Department of Energy (DOE), has installed a real time X-ray system that can "see through" molds and watch defects as they form.

Figure 2. Schematic of the real-time X-ray system.



Experimental Approach

The X-ray system is shown in Figure 1 and schematically illustrated in Figure 2. The system consists of a lead-lined vault and contains a 320 kV power source and a 9-in. diameter image intensifier to capture metal flow images. A second X-ray system consists of a 160 kV microfocus tube and an 8 in.x10 in. rectangular digital detector is used to examine the internal quality of the castings produced. There is an externally controlled pouring cart with a DC motor drive so the pouring rate can be controlled and varied to simulate production pouring rates.

Molten metal is melted and tapped from the furnace into the ladle. The ladle is then moved into the vault and positioned in front of the mold to be poured. External controls are attached to the pouring cart, and the vault door closed. Two cameras are used to observe the pouring operation.

High energy X-rays pass through the mold as the metal is poured, and the fill patterns are recorded as differences in X-ray intensity. The images are normally recorded at 30 frames per second (fps) with a VCR and/or a computer. After recording, the flow and fill events can be reviewed and studied at slower frame rate. Intensity differences in different parts of the mold cavity produce "gray" levels that reflect the locations of metal and air in the metal and the mold.

The video images are processed to analyze metal filling and to evaluate metal front velocity, bubble formation, and oxide formation. Bubbles and metal splashing can be seen because metal attenuates X-rays more than dross or gas in the casting.

Flow contour maps allow metal front velocities to be determined as a function of fill fraction and time. The results can be compared with predictions made by simulations and with guidelines for maximum front velocity. The number of converging metal fronts and the average front velocity are related to the surface and internal quality of castings. These parameters can be traced back to the pouring conditions such as gate design, mold permeability, binder type, pouring temperature, and other variables to determine practical changes that can be made to reduce splashing, gas evolution, and defect formation.

Observations in Lost Foam Molds

Pattern pyrolysis residue is the most difficult issue to be resolved in the lost foam casting process. If the residue produced during pattern pyrolysis is not expelled and captured by the coating, it can produce folds, blisters, and internal pores.

Folds. Folds appear as linear discontinuities where two metal fronts meet but do not completely fuse together. Folds often contain oxides and some foam pyrolysis products. The existence of the fold defect degrades the mechanical and fatigue of the lost foam castings significantly. In some cases, fold defect is also the cause of leak in hydraulic test of the castings.

An aluminum casting with several folds on the surface is illustrated in Figure 3(a). The gray lines are pyrolysis traces, and the black lines outline fold locations. The real time X-ray "video still or frame" in Figure 3(b) illustrates the replacement of the pattern used to produce this casting. This "video still" was extracted from a recording made at 30 frames/second while metal was replacing the pattern. Similar images were extracted at 0.2s intervals (every 6 frames), and metal front profiles are shown in Figure 3(c). The metal front contours in Figure 3(c) were then overlaid on the casting photograph (Figure 3a) to produce Figure 3(d).

Folds consistently formed along metal convergence lines, as illustrated in Figures 3a-3d, and the converging metal fronts entrapped foam pyrolysis products. Fold defects formed when the pyrolysis products failed to escape before metal solidification. Correlations between the metal filling behavior and casting process variables show that this metal front "fingering" is associated with a low degree of pattern fusion and density gradients. The fingering can be eliminated by improving the pattern blowing and fusion cycles.

Blisters and **internal porosity blisters** are thin layers or lines of oxides, carbon, or porosity usually found just beneath the casting surface. These defects are associated with high metal fill velocities. High velocities usually occur when patterns have a low degree of fusion or when the coating has an excessively high permeability.

The photographs in Figure 4 illustrate a casting produced with a pattern having a high permeability coating (67.9 cm^3/

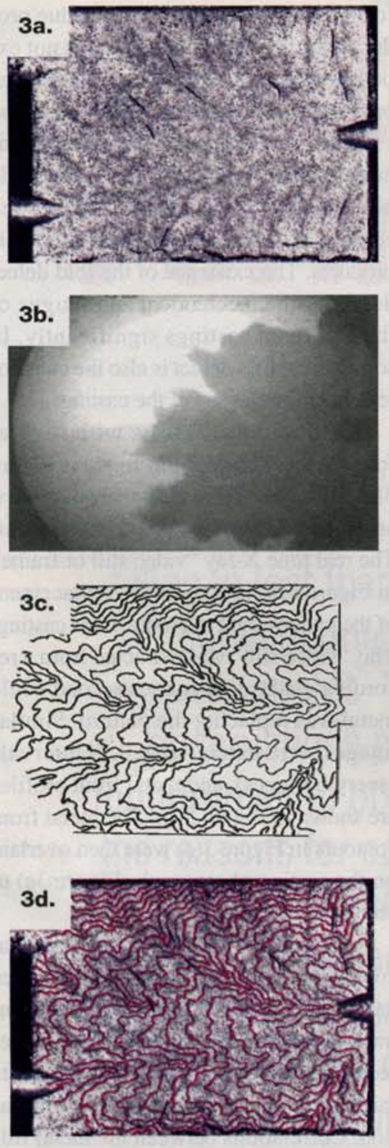


Figure 3: Fold formation in an aluminum casting; a) folds on casting; b) video still of metal enetering mold; c) metal front contour map; and d) superimposed fold map and metal front contour map.

(cm^{2}s)) which produced a high pattern replacement rate. Liquid pyrolysis products were entrapped in the metal, and produced the gas bubbles in the casting, as illustrated in Figure 4(a), when the liquid decomposed to produce gas. The locations of the blister defects are circled, as illustrated in Figure 4(b), and a digital X-ray of the casting exhibiting a trail of porosity is illustrated in Figure 4(c). Excessively fast pattern replacement produced liquid pyrolysis products that could not readily escape through the coating. These produced bubbles as the liquids decomposed. The bubbles floated to produce a line of porosity as illustrated in the X-ray shown in Figure 4(c).

Figure 4: Effect of metal filling behavior on the formation of blisters and pores; a) Video still of metal filling; b) photograph of surface defects; and c) digital X-ray image of casting

Observations in Conventional Sand Molds

Filling open cavity molds can also be examined with the X-ray system. The appearance of furan resin bonded mold containing a 4 in. x 4 in. x 0.5 in. (102 mm x 102 mm x 13 mm) plate is illustrated in Figure 5(a), and the pouring arrangement in the vault is illustrated in Figure 5(b).

The casting has a tapered sprue, a horizontal runner, and a bottom ingate. The gating area ratio was 1:1.1:1.1 to produce a slight choke at the bottom of the sprue. A Class 35 gray iron was poured at approximately 2550° F (1400° C) after inoculation with 0.25 percent silicon as foundry grade FeSi. The vertically split mold halves were clamped using threaded rods through wooden backing boards. There were spacers between the mold and the backing boards to allow gases to escape in a normal fashion. The mold has a pouring basin built into the top, as illustrated in Figure 5(a).

Metal-Mold Interactions. Some molds were poured without a coating, and others were poured after the mold had been coated with an alcohol-based zircon wash. The wash reduced mold permeability, increased the internal pressure in the mold cavity, and reduced the metal fill rate. Metal fill contours under different conditions are illustrated in Figure 6. Metal fill without coating was quite chaotic, as illustrated in Figure 6a. When a coating was applied, metal filling was slower and smoother, as illustrated in Figure 6(b). Coating the mold with three coats of wash produced an even lower mold fill rate as illustrated in Figure 6(c).

Cold shot metal splashing and the formation of metal shot (cold shot) is illustrated in Figure 7(a). Splashing produced by a high metal velocity produced many metal shot. The surface of these shot probably oxidized and then froze when they hit the cold mold. The cold shot were then flushed back into the casting by flowing metal to produce an internal anomalies.

Air Entrapment. Air entrapment was also observed and oxygen in the air reacted with iron to produce metal oxides (reoxidation products) found both on the surface and the interior of castings.

Mold Gas. In addition to entrapped air, mold gas from residual volatiles in the coating and/or the sand binder produced gas defects. The pressure of the gas was sufficiently high that the molten metal was pushed away from the mold wall, to produce depressions on the casting surface, as illustrated in Figure 7(b). Some gas was also present near the top surface of the casting as illustrated in Figure 7(c). If the metal were poured hot enough, this gas might float out of the casting rather than appearing as a sub-surface void.

Casting Quality

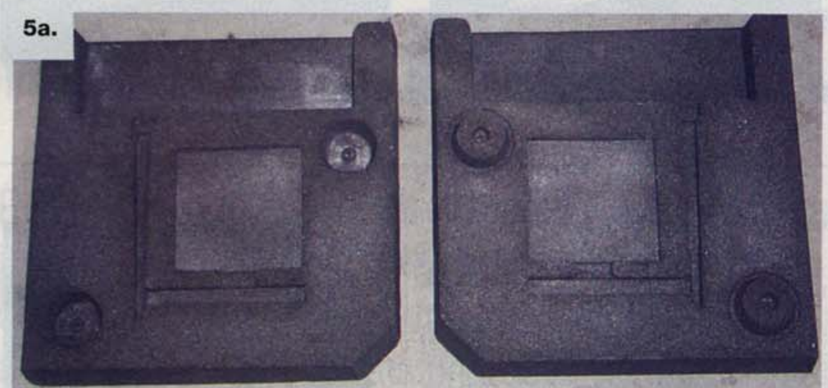
The internal and surface quality of some castings poured under different conditions is illustrated in Figure 8. An X-ray image of a casting produced with metal swirling into the cavity is illustrated in Figure 8(a). Images about castings produced with various amounts of mold wash are illustrated in Figures 8 (b), (c), and (d). The casting surface quality improved when mold wash was applied, but the number and size of internal pores was increased, as illustrated in Figures 8 (b) and (c). The gas pores were a result of the mold having inadequate permeability. When residual volatile materials were involved from the coding, they could not readily escape and this produced pores and scars as illustrated in Figures 8(c) and 8(d).

Technology Extensions

Real time X-ray provides a way to see events occurring in molds and determine the root cause of defects such as porosity from entrained air, wash decomposition, shot, folds, and other defects not illustrated in this article. The filling of molds, such as those made on a Hunter or small Disamatic, can be viewed directly with the X-ray system, but the system becomes even more valuable when used to compare fill patterns with simulation results. When verified for simple cases, the codes can be used with confidence to make calculations on castings larger than can be viewed in the X-ray vault.

X-ray studies of metal filling in real time can be used to remove much guesswork about anomaly causes and allows remedial action to be taken on the real

5a.



5b.

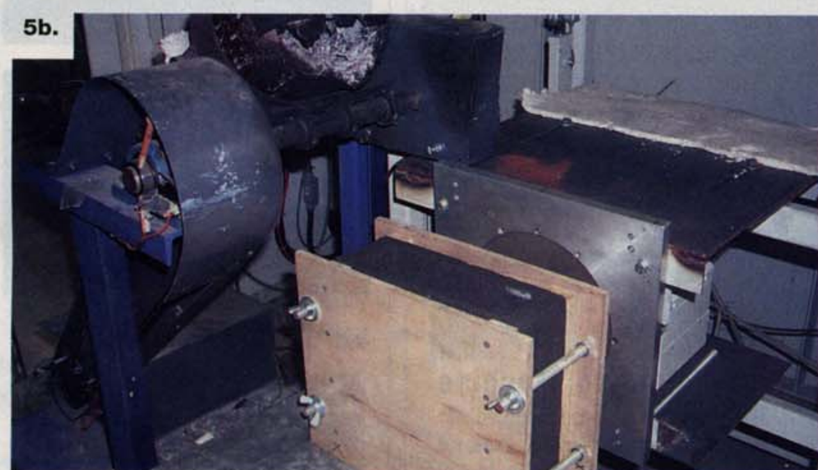


Figure 5.: Conventional sand casting; a) furan resin bonded mold halves; and b) pouring arrangement in the lead vault.

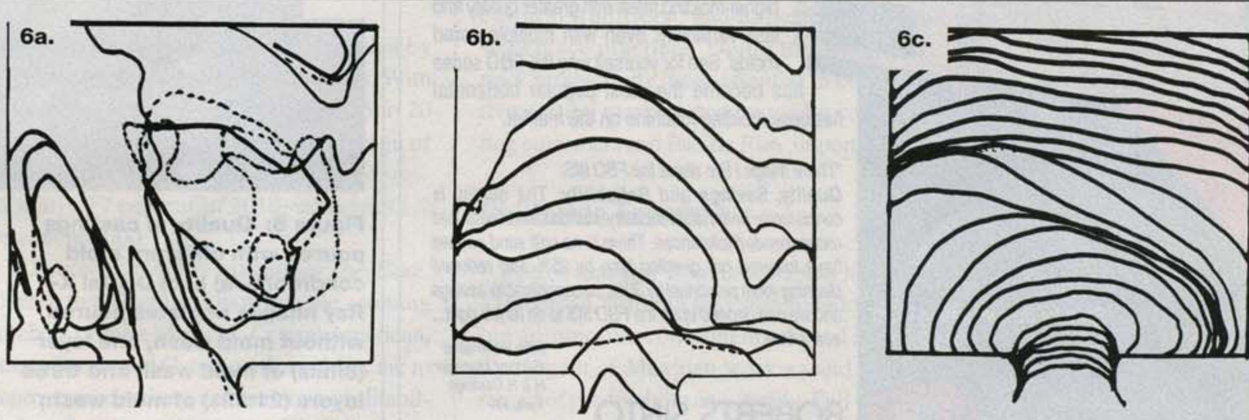


Figure 6. Metal front contour maps. Fill lines were traced at 0.1 sec. time intervals: a) no coating; b) one coating layer; and c) three coating layers.

Figure 7: Observations during mold filling; a) cold shot and air entrapment; b) mold gas entrapment during filling; c) Mold gas after metal filing.

causes, not assumed ones. More research is needed, and future work will be conducted to extend defect analysis and remediation to consider:

- Gating system design for various casting designs.
- The effect of filters (type, size, orientation, and location).
- Defect formation in permanent and ceramic (investment) molds.
- Metal filling effects on casting properties including machinability, and mechanical and fatigue properties.
- Continued validation of computer models.

Figure 7 in this article depicts an X-ray sequence showing metal filling a mold. To see an actual video of a mold filling, log onto http://www.uabcastingengineeringlab.com. The files are large, so to watch them download them onto your computer and play them off your hard drive.

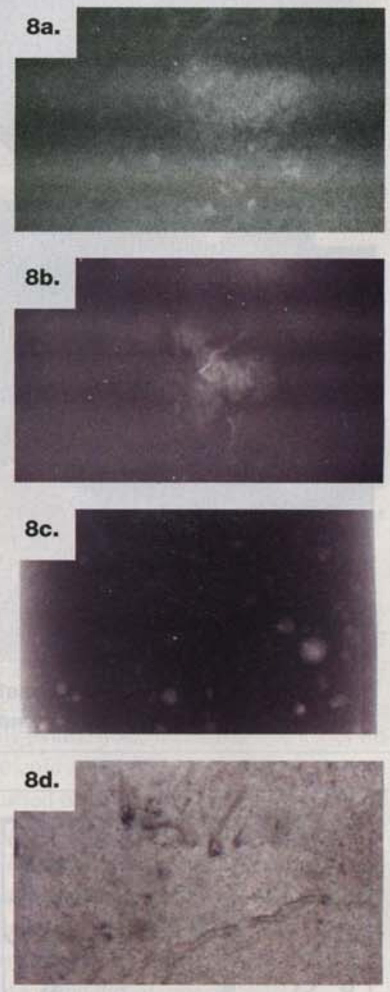


Figure 8: Quality of castings poured with different mold conditions. a) b) c) Digital X-Ray images of plates poured without mold wash, one layer (8mils) of mold wash and three layers (21mils) of mold wash; d) Photograph of the as-cast surface.