Innovative use of Computer Simulation and Real Time X-ray Technology to optimise Steel Gating Systems

Abstract

One of the most important criteria for success in producing clean steel castings is the influence of the gating system. A gating system must be designed to smooth metal flow to the mould cavity and minimise the creation of turbulence to avoid the formation of oxide macro inclusions that contribute substantially to the cost of steel castings. Furthermore, the gating system should induce efficient separation of slag, eroded ladle refractories and eroded moulding materials to prevent these from entering the casting cavity and becoming casting defects.

For many years, filters have been incorporated in gating systems for this purpose. The broad use of filtration has been limited however by constraints associated with poor filter priming, or the chilling effect that causes metal to freeze off at the filter surface before steady state flow can be achieved. (1) There is also considerable debate concerning the best way to apply filters for maximum efficiency. Recent FOSECO studies confirm much of what has long been suspected about good gating and filtration practice. They have also led to new foam filter development that allows greater flexibility in application practice and smoother metal flow to the mould and increased yield.

Using water flow modelling, fluid flow simulation and real-time X-ray video film sequences, this paper illustrates current optimum gating practice for both conventional "in-line" gating systems and direct pour systems, using both geometrically simple and complex castings.

Introduction

The FOSECO Companies have historically focused on the impact of gating and feeding system designs and components such as filters and sleeves on the filling and solidification of ferrous and nonferrous castings. In recent years, modelling, simulation and video recording techniques have been used to study the impact of gating system design and filtration media on flow and turbulence, especially with oxidation-prone alloys such as carbon steel and low-alloy steel.

This work has been strongly influenced by earlier work done by others, including a widely followed set of aluminium casting guidelines that makes gating design recommendations based on computer modelling and X-ray studies of aluminium casting published by Professor John Campbell, University of Birmingham, UK. (2) FOSECO, in conjunction with several universities and other technical organizations, has expanded upon this work using steel and has undertaken similar investigations focused on conventional gating systems as well as on direct pouring.

Plate castings were selected as the initial test objects for evaluating the flow modification properties of simple gating and direct pour systems. A geometrically complex valve casting was later utilized in a more practical evaluation of the flow modification properties and the benefits of foam filters, using a variety of filter prints and direct pour positions.

Examples presented in this paper include:

- Water model studies of a plate casting, bottom- and top-gated, that contrast unfiltered and filtered arrangements
- Real-time X-ray studies of a top-gated plate casting that contrast the flow characteristics of steel in a mould cavity using unfiltered and filtered arrangements
- Mould filling simulations of a valve casting, with conventional gating including in-line ceramic foam filters, and direct pour units with ceramic foam filters, using X-ray study confirmation
- Mould filling simulations of a valve casting, incorporating a new type of foam filter in various conventional gating and direct pour arrangements, to determine optimum gating practices.

Water Model Studies of a Plate Casting

Early water model flow studies for aluminium used simple, transparent, plate-shaped cavities in top-gated and bottom-gated configurations. (3) Typically, for gravity casting of aluminium and casting of steel, non-pressurized gating systems are used to minimize the velocity of the metal as it passes through the ingate and enters the mould cavity. In these systems, the sprue is normally the choke, with proportional increases in the cross sectional area of the runners and ingates to reduce metal velocity and compensate for frictional flow rate losses through the runners and ingates.

These water "moulds" were prepared using common, non-pressurized gating ratios, including 1:2:2 and 1:4:4. Liquid soap was added to the water to make the flow patterns more visible during the filling of the model moulds. Video film sequences at normal speed and in slow motion were taken as a series of different gating system layouts and cross sections was filled.

Figure 1a illustrates unfiltered flow with a top-gated mould configuration. Considerable turbulence, swirling and air entrainment are visible as the water falls into the mould cavity. Figure 1b illustrates unfiltered flow entering through a bottom-gated mould cavity. While bottom gating produces smoother entry and filling of the mould cavity, considerable turbulence remains.

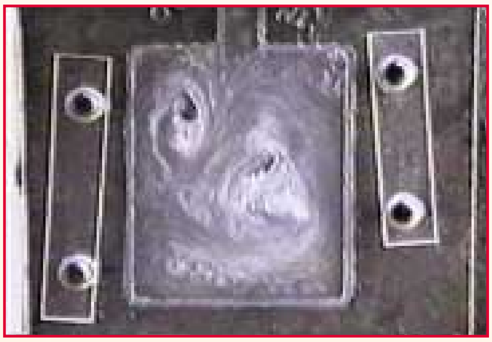

Figure 1a: Top-gated water-model plate mould, unfiltered flow

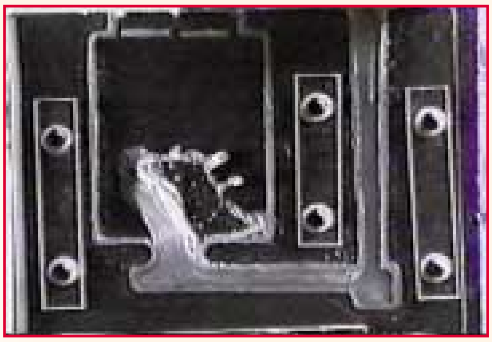

Figure 1b: Bottom-gated water-model plate mould, unfiltered flow

To get smooth, even filling, the velocity of the molten material must be reduced as it enters the mould cavity. This can be achieved by redesigning the gating system with a smaller sprue or by increasing the area of the runner, using the 1:4:4 gating ratios. It is also possible to reduce metal velocity by using a filter in the gating system. Ceramic foam filters are normally placed at the base of the sprue, where the metal is the hottest, to facilitate filter priming. (This, however, reduces filtration effectiveness, as we shall see later.)

In Figure 1c, the water enters the mould cavity through a bottom gate that includes a 75 x 25mm/10ppi foam filter. There is virtually no visible turbulence because of the flow modifying effect of the filter. As the water passes through the tortuous path within the filter, its velocity and turbulence are significantly reduced.

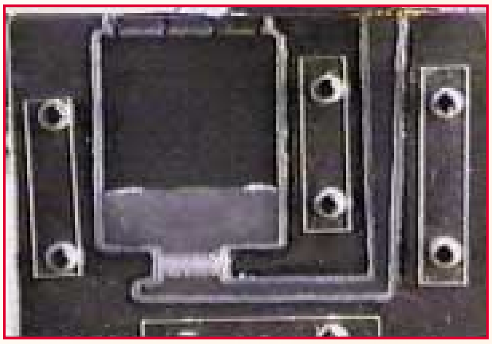

Figure 1c: Bottom-gated water-model plate mould, with foam filter at ingate

It is assumed that the reduction of velocity and turbulence minimizes the formation of oxide macro inclusions that compromise the physical properties and the surface appearance of steel castings.

Real-time X-ray Studies

X-ray studies have been widely used to examine metal castings. (2, 4) Refinement of a workable, real-time, X-ray technique for steel casting has enabled the direct imaging of molten steel as it enters a mould cavity. FOSECO conducted extensive evaluations of the effect of various in-line filter positions and filtered direct pouring on flow modification in partnership with the Castings Technology Institute, Sheffield, UK. (5)

The real-time X-ray equipment is contained in an X-ray bunker and remote controls are used to operate a bottom-pour ladle inside the bunker. X-rays are produced by a 2.4 MeV Van de Graaff X-ray source capable of penetrating castings up to 200mm thickness. X-ray images are generated on a phosphor screen and captured by video recording equipment.

A simple plate casting measuring 600 x 400 x 60mm with an approximate weight of 115 kg was used. A vertically parted sand mould was designed to accommodate the requirements of the X-ray process. Since minimal mould wall thickness was critical to the X-ray process, the mould was supported within a specially designed steel sheet frame.

Figure 2a shows molten steel entering the cavity through an unfiltered top gate. Surface turbulence and gas bubbles are clearly visible as the mould

Figure 2a: Top-gated plate-mould real-time X-ray, unfiltered

cavity fills. The bubbles are caused by the high velocity of the falling metal stream that entrains air as it enters the cavity. The metal splashes on the bottom of the mould, is reflected upward from the corners, and falls back into the middle area. The entrained air coalesces to form bubbles that then rise to the surface. This turbulence greatly enlarges the amount of molten metal surface area that is exposed to oxygen in the air, leading to excessive reoxidation. Notice that the X-ray example concurs with the unfiltered top-gated water model findings discussed previously.

In Figure 2b, a direct pour sleeve that incorporates a 75 x 25mm/10ppi ceramic foam filter is used. Examination of the metal exiting the filter discloses that it has coalesced into a single, solid stream, thereby reducing the amount of liquid metal surface area exposed to air. The filtered metal flow fills the cavity more smoothly, with very little rolling motion and no bubbles rising to the surface. This, too, confirms the water modelling results presented previously, where addition of a filter considerably reduced the amount of turbulence.

Figure 2b: Top-gated plate-mould real-time X-ray, ceramic foam filter in direct pour sleeve

Mould Filling Simulations and X-Ray Confirmation

The use of computer simulation to model the filtered casting process is a valuable tool that enables foundries to avoid the expense of trial-and-error casting engineering. Like all computer analysis, the validity of these simulations depends heavily on the accuracy and quality of the input data, particularly the effect that filters have on molten metal flow.

Fluid flow through a filter is dependent upon the density and viscosity of the fluid and the configuration and porosity of the filter material. Using pressure drop data obtained from water modelling studies, FOSECO has developed flow coefficients for STELEX foam filters that have significantly increased the accuracy of computer flow simulations. (6) Computer simulations, based on these coefficients, and X-ray studies of a production steel valve casting were done concurrently to demonstrate the validity of computer simulation in predicting casting fill characteristics.

To conduct the X-ray studies, it was again necessary to create a special mould, small enough to allow X-ray penetration. This was accomplished using the REPLICAST process, developed by the Casting Technology International. It involves dipping a polystyrene replica of the valve casting in successive coats of a refractory slurry material that is then dried and fired. The fired shell is supported in a casting box filled with unbonded sand.

In Figure 3a, a filtered direct pour unit is used. Direct pouring eliminates the need for a pour cup, downsprue, filter print, runner system and one feeder. The pour weight of this configuration is 113 kg. This simulation shows the flow at 2 seconds after pouring has begun.

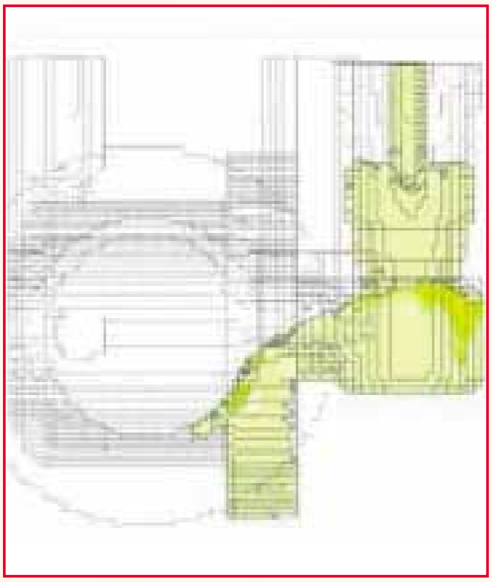

Figure 3a: Computer simulation of metal flow in valve casting with a KALPUR direct pour unit at 2 seconds

Figure 3b shows an X-ray image taken during the filling of the direct pour mould, also 2 seconds after the pouring has begun. While it is difficult to discern from the still images used in this paper, both the simulation (Figure 3a) and the X-ray image are in close agreement. Further validation of the accuracy of the filter model lies in the fact that the actual pour time as experienced in the foundry only differed from the predicted time by 0.3 seconds.

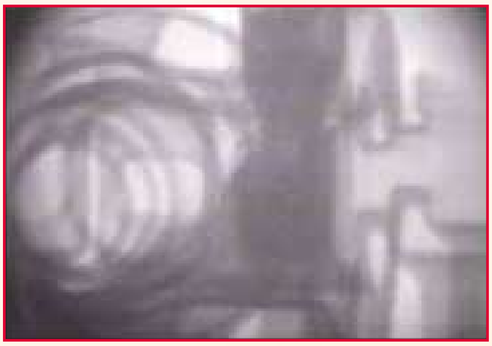

Figure 3b: Real-time X-ray study of metal flow in valve casting with filtered direct pour unit at 2 seconds

The second configuration (Figure 4a) simulates flow in a conventional gating system at 2 seconds after pouring has begun. It incorporates a single, in-line, STELEX ZR ceramic foam filter at the base of the downsprue, with two runners leading to the ingates. The pour weight of this configuration is 125 kg. Notice that the use of a conventional filtered gating system increased the pour weight by 10%, thereby decreasing the yield.

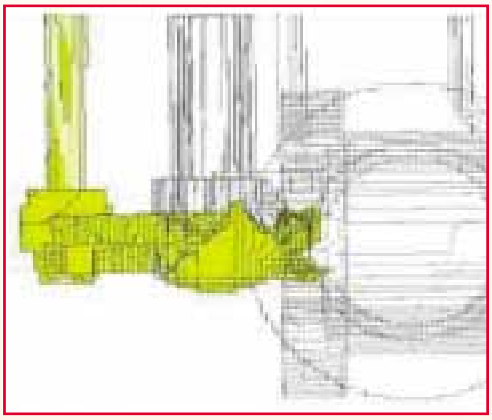

Figure 4a: Computer simulation of metal flow in valve casting with in-line filter at 2 seconds

Figure 4b shows an X-ray image taken during the filling of the conventionally gated mould, also 2 seconds after pouring has begun. Again, there is good agreement between the simulation and the X-ray view. The predicted fill time was within one second of the predicted pour time.

Based on the close agreement of the simulation and X-ray results in this study and others, we have concluded that properly prepared simulations using accurate filter data may be relied upon without the need for X-ray confirmation.

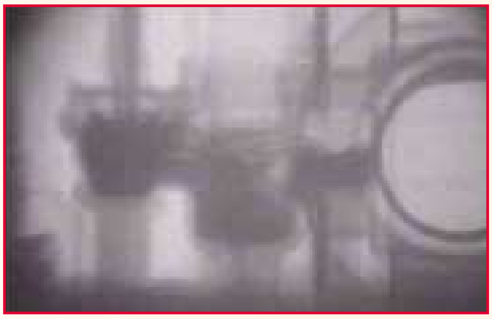

Figure 4b: Real-time X-ray study of metal flow in valve casting with in-line filter at 2 seconds

Product Development

Many investigations have documented the efficient removal of oxide macro inclusions such as slag, refractories and sand, from metal streams using foam filters. These investigations and additional simulation work have led us to believe that, for steel, optimum filtration performance can be achieved by minimizing the velocity and turbulence of liquid steel in the gating system through positioning filters very near the ingates of the mould cavity.

Until recently, this has not been practical, particularly when using zirconia-based STELEX ZR ceramic foam filters in the casting of oxidation prone and skin forming alloys such as carbon and low-alloy steels. The heat capacity of conventional zirconia-based foam filters requires that they be positioned immediately at the base of the downsprue where the metal is hottest, to facilitate priming, or to avoid "freezing off", before steady state flow is achieved.

While higher pouring temperatures can be used so that the metal remains hot enough to "prime" filters located closer to the ingates, this is costly and exacerbates the problems of metal oxidation. Although placing the STELEX ceramic foam filter in a KALPUR direct pouring unit usually resolves the priming problems, the density of the ceramic filter sometime prevents it from floating after pouring has stopped; as a result, shrinkage can be encountered beneath the filter.

FOSECO has developed a highly stable, non-ceramic refractory filter, STELEX PrO, (figure 5) which exhibits high-temperature strength, creep resistance and thermal shock resistance to withstand the impact of molten steel. Most importantly, it does not absorb excessive heat, thus preventing priming problems and providing the casting engineer with new flexibility in gating design. In addition, this low-density filter increases the likelihood of filter floatation in direct pour applications after pouring, thus preventing shrinkage below the filter. The discussion that follows examines the application and performance of this new filter material.

Figure 5: STELEX PrO non-ceramic refactory filters

Optimum Gating Design Practice Studies

To determine the optimum gating design practices for filtered in-line and direct pour configurations, the same valve casting was again chosen, this time with two of the risers combined to improve yield. Flow simulations based on accurate filter flow data were performed using a variety of filters, filter prints and filter positions.

In one set of studies, the "best quality practice" solution was the one that produced the lowest simulated velocity and turbulence as the metal entered the casting cavity. In another set, the "best yield practice" solution was the one that produced the best percentage yield, defined as casting weight divided by pour weight.

Best Quality Practice

Low in-gate metal flow velocities and minimal flow turbulence are desirable characteristics of a steel casting gating system that minimizes oxide macro inclusions and related defects caused by sand erosion and reoxidation. Several gating designs were simulated to evaluate these characteristics, including (a) an unfiltered system, (b) a conventional ceramic foam filter system, (c) a system employing the STELEX PrO foam filters, and (d) a system employing a KALPUR side-risered direct pour unit. Low alloy steel was used, poured at 1580ºC.

Figure 6 shows the simulation of the conventionally gated test valve poured without any filtration. Notice the high velocity, indicated by the white and yellow areas, suggesting the possibility of the formation of oxide macro inclusions caused by sand erosion and reoxidation. In addition, without filtration, it is probable that oxide macro inclusions originating both outside and inside the mould will end up in the casting cavity as defects. This configuration has a casting weight of 57kg and a pour weight of 109kg, giving it a 52% yield.

Figure 7: Simulation of metal flow in conventionally gated valve casting with zirconia-based ceramic foam filter positioned at base of downsprue

The best in-line gating design practice, (figure 8), is seen where two smaller STELEX PrO 55 x 55 x 20mm/10ppi filters are vertically oriented and located close to the mould cavity. This gating arrangement is now possible because of the lower heat capacity and density of the filter. It can be seen, by the minimal amount of white area visible, that this arrangement results in the least amount of turbulence as the metal enters the mould cavity, thus minimising the potential for the formation of oxide macro inclusions that result in casting defects. The filters are also in an optimal position to intercept slag, refractories and sand. This pour weight is 108kg, with a yield of 52%.

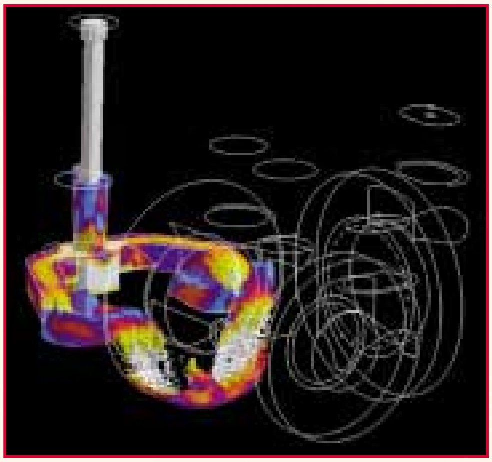

Figure 6: Simulation of metal flow in conventionally gated valve casting without filtration

Figure 7 shows the gating designed with a 75 x 75 x 25mm/10ppi, zirconia-based STELEX ZR ceramic foam filter printed at the base of the downsprue to avoid priming difficulties.

While this in-line filter arrangement greatly reduces the velocity of the metal (indicated by the reduced amount of white and yellow areas), it still results in some turbulence as the metal reaches the casting cavity and leaves the possibility that oxide macro inclusions will be formed. This configuration has a pour weight of 107kg, and a yield of 52%

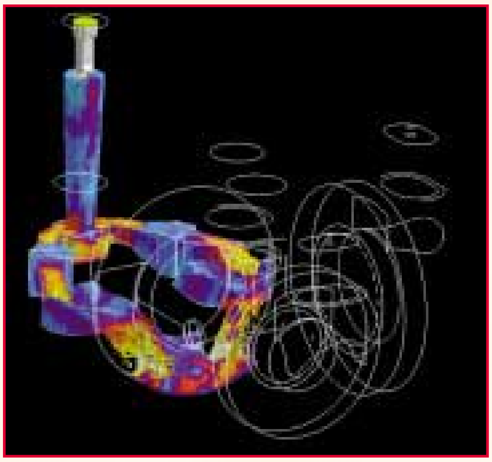

Figure 8: Simulation of metal flow in conventionally gated valve casting with two STELEX PrO filters vertically oriented and positioned close to the mold cavity

In an alternative best quality gating design practice, (figure 9), one of the side risers is replaced with a KALPUR direct pouring unit that includes a STELEX PrO filter; an appropriately sized feeding basin is positioned under the direct pour unit. Of all the designs, this configuration produces the lowest overall casting velocities and minimum turbulence, as evidenced by the complete absence of white in the velocity field. This configuration also has a pour weight of 108kg and yield of 52%.

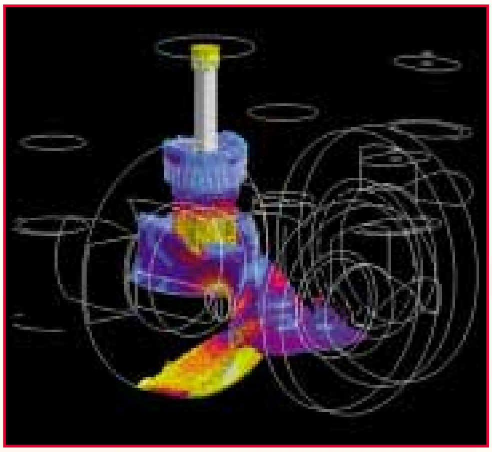

Figure 9: Simulation of metal flow in valve casting with one side riser replaced with a direct pour unit including a STELEX PrO filter

Best Yield Practice

In many cases, the use of filtered direct pouring can also reduce the poured weight of the casting and increase yield by eliminating conventional in-line gating system components. In Figure 10 a & b, the direct pour unit, including a STELEX PrO filter, is placed in a top-riser position and has a pour weight of 100kg. Notice that the yield for the top-riser arrangement is optimised to 57%, compared to 52% for the other casting configurations.

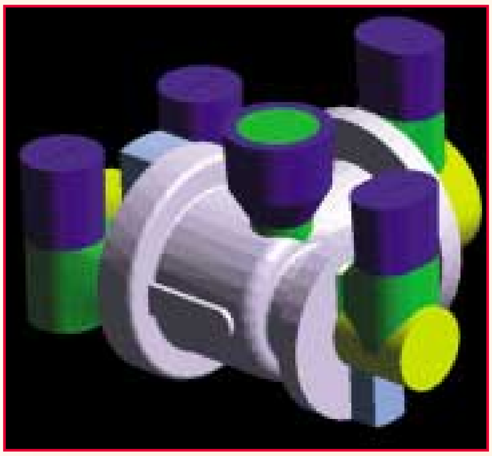

Figure 10a: Configuration of valve casting with direct pour unit in top-riser position

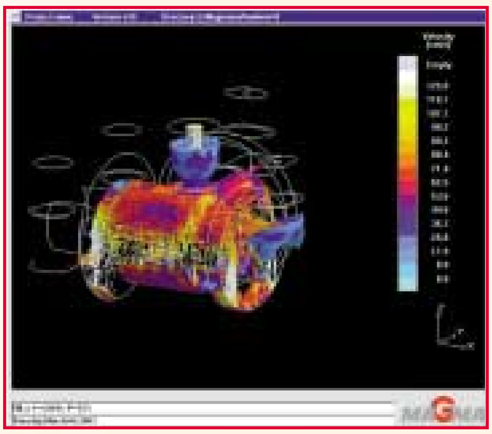

Figure 10b: Simulation of metal flow in valve casting with direct pour unit in top-riser position

However, by placing the direct pour unit in a top-riser position, the height of the metal drop is increased substantially. The geometry of the casting becomes an important consideration when employing this type of approach, and not all castings can successfully be made in this fashion. Care should be taken to ensure that the quality of the casting is not compromised greatly when employing a top-risered direct pour unit.

Conclusion

The use of water models, real-time X-ray visualization and computer simulation are all useful foundry tools. While water models and real-time X-ray may not be practical for the production foundry, they have proven to be invaluable in the evolution of filter product development that has led to greater flexibility in filter application and optimum filtration performance. They have also confirmed the validity of computer simulations that today's modern foundries have grown to depend upon to avoid the expense of trial-and-error gating system engineering.

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* The REPLICAST process is a patented process exclusive to the Casting Technology International, UK.