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Lucas Archer, Richard A. Hardin & Christoph Beckermann

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COUNTER-GRAVITY SAND CASTING OF STEEL WITH PRESSURIZATION DURING SOLIDIFICATION

Lucas Archer, Richard A. Hardin, and Christoph Beckermann
Department of Mechanical and Industrial Engineering, University of Iowa, Iowa City, IA, USA

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Abstract

Counter-gravity filling and pressurization during solidification have been separately shown to improve casting quality in sand cast steel. Studies and industry practice show that counter-gravity filling increases the yield and reduces reoxidation inclusions. Other studies show pressurization during solidification has the potential to increase the feeding effectivity of risers, which leads to a reduction in centerline shrinkage. In the present study, a method for sand casting steel is developed that combines both practices. Casting simulations are used to determine key events during the process. Counter-gravity filling of a sand mold with liquid steel is performed by linearly decreasing pressure to a value of 0.053 MPa and holding this pressure for 40 s. After the vacuum pressure is released, the entire system is pressurized to a maximum pressure of 0.35 MPa, 220 s after the start of the filling process. The casting method is applied to cylindrical bar castings. Radiographic and dye penetrant inspection of the bars shows no detectable centerline porosity forms when the casting system is pressurized, unlike the gravity-poured control castings.

Keywords: *steel casting, sand casting, counter-gravity casting, pressurization*

Introduction

Counter-gravity sand casting of steel with pressurization during solidification (CGPS) has the potential to reduce inclusions and porosity in conventional steel sand castings. By using a counter-gravity filling process, air entrainment can be reduced by eliminating the fall of liquid metal into the sprue and waterfalls within the mold cavity.[1] Reoxidation inclusions form when the deoxidized steel is exposed to oxygen in the entrained air. An additional advantage of counter-gravity filling is the elimination of the sprue and runner of traditional steel casting systems, which increases the yield of the casting process. An airtight casting process vessel is required for counter-gravity filling; the vessel can be readily used to apply pressure to the casting system, while the steel is solidifying. Pressurization during solidification has been shown to increase the feeding distance of the risers,[2–6] which in turn reduces the centerline shrinkage porosity. The objective of the present study is to develop and test a system for casting steel in a sand mold that utilizes the benefits of both counter-gravity filling and pressurization during solidification.

For the past 30 years, counter-gravity casting of steel has been a proven method to obtain quality parts. In 1982, Chandley et al.[7] patented a counter-gravity steel casting process. In this process, a gas permeable sand mold was placed within a chamber. The mold's lower surface was placed directly on top of the liquid metal reservoir with the gates to the casting cavity submerged. Vacuum pressure was applied to the top of the mold, which filled the mold cavities with molten steel. In this method, multiple disconnected parts were cast without the use of a sprue or

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runner. One shortcoming of this process was that the bonded sand in contact with the melt reservoir failed after a short time for high melting temperature alloys, such as steel. The maximum vacuum pressure was limited to 0.09 MPa to prevent penetration of the gas permeable mold by the liquid metal. This in turn limited the maximum height of the castings that could be filled to 203 mm. Chandley et al.[8] further refined their counter-gravity casting process with the introduction of the loose sand vacuum-assisted casting process (LSVAC). A thin-shelled investment mold was used rather than a bonded sand mold. The molds were then backed with loose sand, hence the name. The thinner molds allowed for more castings per process cycle, as well as more freedom in mold orientation within the vacuum chamber. The LSVAC process produces excellent thin-walled stainless steel castings, such as automotive exhaust manifolds. However, manufacturing investment molds requires a greater financial investment in process equipment than resin-bonded sand molds.

Griffiths et al.[9] investigated the reproducibility of mechanical properties for low-alloy steel investment plate castings produced from four different casting processes. Tensile test bars were generated from the plate castings. Two gravity-poured investment molds were used. One mold was filled with liquid steel poured directly into the part cavity. The second gravity-poured casting included a conventional gating system with a runner that filled the part cavity from below. Two counter-gravity processes were used in addition to the gravity-poured molds. The first of these was developed by Hitchiner Manufacturing Co., Inc., and it is similar to the LSVAC process. In this process, metal is drawn up a large central sprue by vacuum pressure and multiple parts are filled. When the gates to the parts have solidified, the vacuum pressure is released and the metal remaining within the sprue falls back into the furnace. The second counter-gravity process tested was the C^3 method, which was also developed by Hitchiner. In the process, an investment mold is filled in the same way as the first process, but during solidification, centrifugal force is used to assist the feeding of the parts. After the centrifugal casting process is complete, the metal remaining in the sprue is returned to the furnace. Griffiths et al. obtained ultimate tensile strength and percent elongation values from the tensile bars and developed Weibull modulus plots from the data. They used the Weibull modulus to quantify the variability in measured material strength. By comparing the Weibull modulus between processes, they found that both counter-gravity methods had significantly less casting-to-casting variability than the two gravity-poured methods. It was speculated that the decrease in variability occurred due to the decrease in splashing and turbulence during filling and from cleaner steel drawn from the lower half of the furnace by the counter-gravity process.

Previous work investigating the effects of pressurization during solidification for sand cast steel used pressure applied to the top of risers. Early work by Jazwinski and Finch[2] in 1945 used gas-producing cartridges in blind risers as a source of pressure. The cartridges released the pressure after an adequate shell had formed on the riser, so that pressure was applied only to the liquid at the top of the riser. It was found that pressurizing the risers increases the casting yield because smaller pressurized risers perform comparably to larger non-pressurized risers. One criticism of this method was the lack of pressure control using gas cartridges and the particular method used in the study was not pursued further. However, the yield increase gained motivated further study of pressurization during solidification processes.

Rather than gas cartridges, Taylor[3] utilized a pipe extending into the riser cavity and used nitrogen gas to pressurize the riser. Again, the riser was pressurized after a significant shell had formed to contain the solidifying liquid. Taylor's method allowed for better control over the magnitude of the pressure over time. A variety of casting shapes were tested and showed that the pressurized riser process produced sound castings occasionally, whereas the non-pressurized riser process did not. Unfortunately, the effectiveness of the pressurized riser process to reduce porosity was not consistent.

More recently, Hardin et al.[4] performed a series of experiments, which compared steel plate sand castings produced with and without pressurizing the risers. A riser cap was used to contain the pressure, and argon was applied as the pressurization gas through a fused silica tube. A variety of pressure schedules were used in each trial with the applied gauge pressure ranging from 0.10 to 0.19 MPa. Pressurization of the riser was found to have increased the feeding length of the riser by a factor of nearly five. The experiment concluded that centerline shrinkage porosity could be reduced by pressurizing the riser. Following pouring, a time delay of the pressure application was necessary in order to prevent casting surface rupture and mold penetration. It was recommended that the solid fraction of the casting surface be at least 0.7 when pressure was applied. This criterion was found to prevent breakout of the casting while providing an adequate window of time for the pressurization to enhance the risers' feeding of the solidification shrinkage.

Pressurization has also been explored in cast metals other than steel. Berry et al.[5,6] successfully demonstrated a reduction in centerline shrinkage porosity in aluminum castings by pressurizing the risers during solidification. Berry and Watmough[5] investigated applying pressure to improve the soundness of two aluminum bar-shaped sand castings of different lengths. Both castings featured a riser at one end of the bar and a plaster cap to seal the top of the riser. To prevent metal penetration into the mold, pressurization of the riser was delayed 30 s and 2 min for the shorter and longer castings, respectively. Gauge pressures

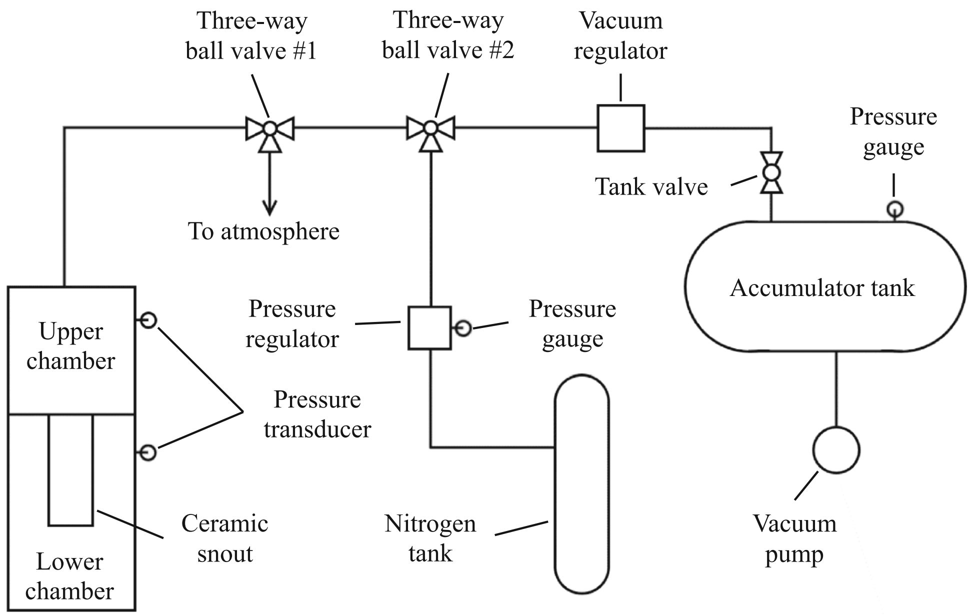

Figure 1. Diagram of vacuum and pressurization lines, and equipment used in the CGPS casting process.

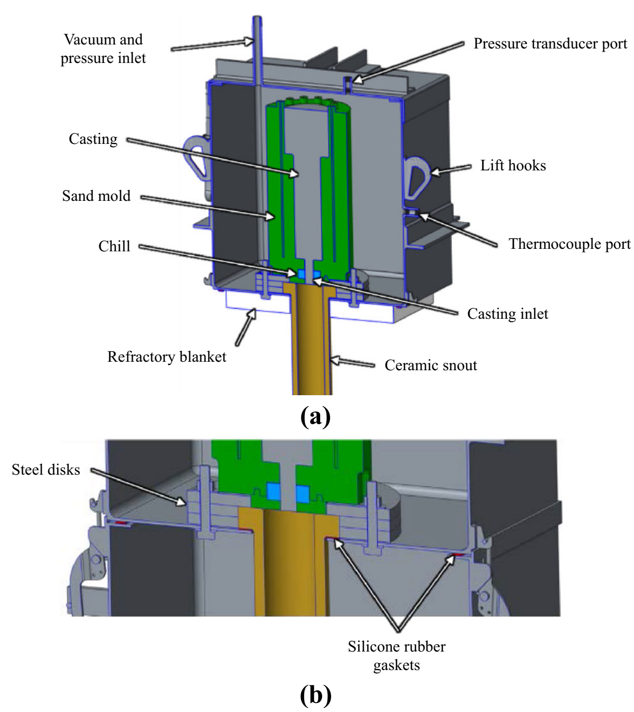

Figure 2. (a) A cut view of the CAD model of the upper chamber and interior. (b) Cut view of the upper chamber sealed to the lower chamber for the pressurization process. (b) Close-up view of the sealing mechanisms used.

of 0.07 and 0.14 MPa were found to reduce the amount of porosity within the shorter and longer castings, respectively. In another study,[6] it was demonstrated that an applied pressure of 0.36 MPa reduced the casting porosity

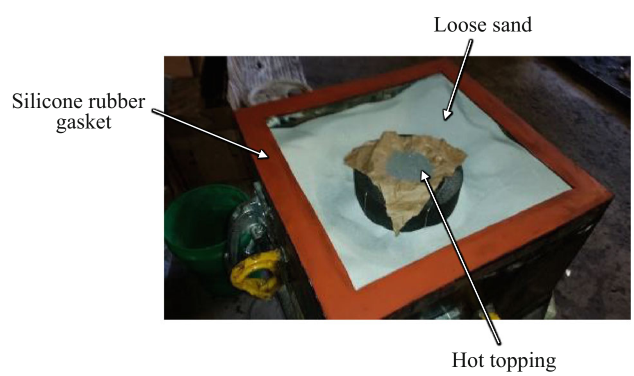

Figure 3. Upper chamber immediately before being sealed. Volume outside of mold is filled with loose sand, and hot topping is positioned on top of the riser.

level to 0.5%, while the porosity level in non-pressurized castings was 1.5%.

While both counter-gravity filling and pressurization during solidification have been separately researched for steel alloys, the authors have found no literature on combining the two processes in steel sand casting. For this study, a process was developed that utilizes counter-gravity filling and pressurization during solidification for casting steel alloys in sand molds. In this casting process, a sand mold is placed within an airtight vessel and raised over a pool of molten steel, and vacuum pressure is used to draw liquid steel up a ceramic tube (herein after referred to as a snout) and into the sand mold. After the inlet to the mold has solidified, the vacuum pressure is released and the vessel is moved away from the melt and sealed atop a second vessel. Then, the entire system is pressurized, while the casting is

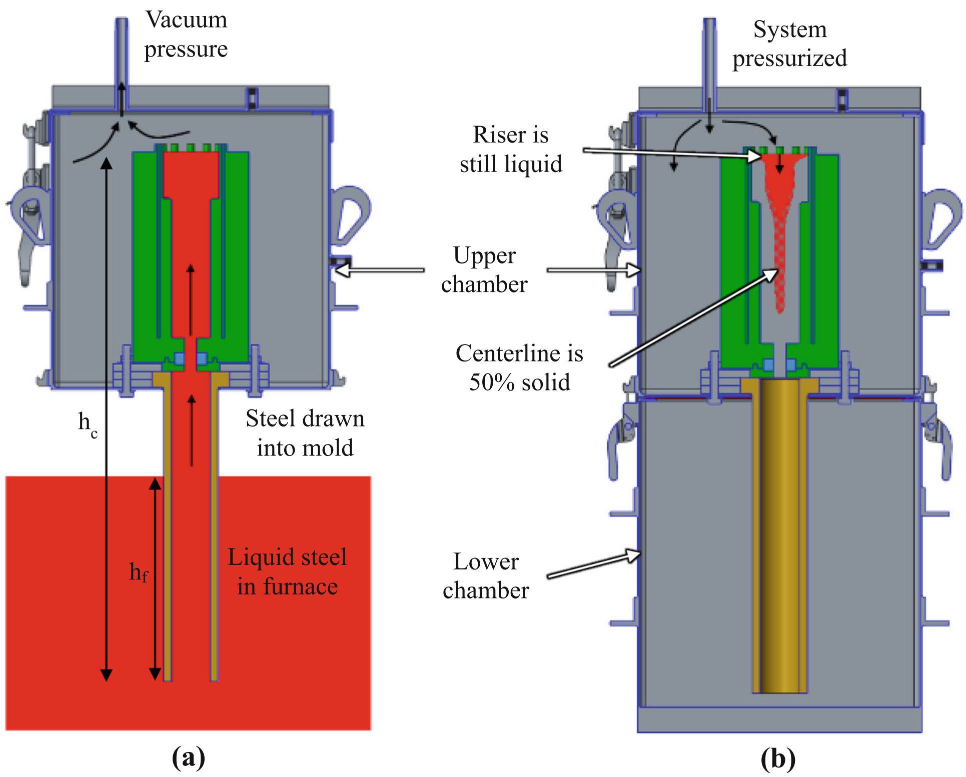

Figure 4. Illustrations of the CGPS process. (a) First, liquid metal is drawn into the mold with vacuum pressure. When the inlet has solidified, the upper chamber is moved from the furnace and sealed to the lower chamber. (b) After the centerline of the casting is 50% solid, the entire system is pressurized.

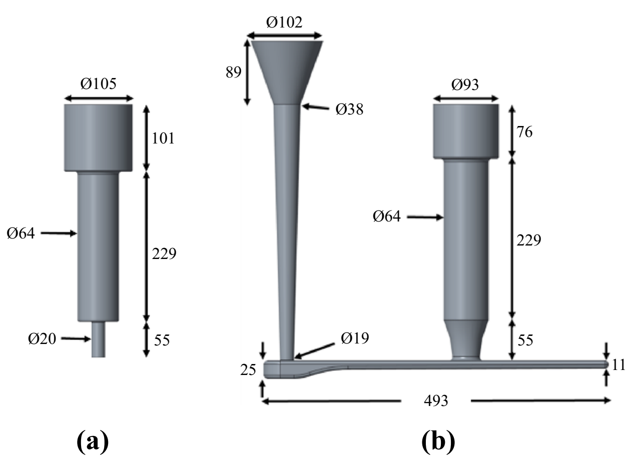

Figure 5. Geometry of the (a) CGPS casting and (b) gravity-poured control casting. All dimensions are in millimeter.

solidifying. An experiment performed to test the process is described in detail below. Gravity-poured control castings were produced with no pressurization, and their shrinkage porosity levels are compared to a casting made with the CGPS process. While previous work has shown that counter-gravity filling improves casting quality,[8,9] the current study only evaluates the reduction in centerline porosity from pressurization during solidification. Oxide inclusion levels were not measured for either gravity-poured castings or the casting produced by the CGPS process.

Experimental Design

A diagram of the system used for the experiment is shown in Figure 1. The overall casting process is as follows: First, a sand mold is placed into the upper chamber, as shown in Figure 2a, and the remaining space in the chamber is filled with loose sand, as shown in Figure 3. The entire chamber is raised above an induction furnace filled with molten steel. The three-way ball valve #1 is turned to atmospheric pressure to prevent a pressure build up within the upper chamber as the fused silica ceramic snout is lowered directly into the molten steel. The three-way valve #1 is returned from atmosphere to the main line. The pressure within the chamber is steadily decreased using the vacuum regulator, drawing liquid steel up the snout and into the mold cavity, as illustrated in Figure 4a. An accumulator tank is used to “store” vacuum pressure because the vacuum pump alone cannot provide the flow rate required to evacuate the upper chamber before the casting begins to solidify. The vacuum regulator maintains the vacuum pressure at a predetermined level keeping the mold full until the inlet below the casting solidifies. Once the inlet

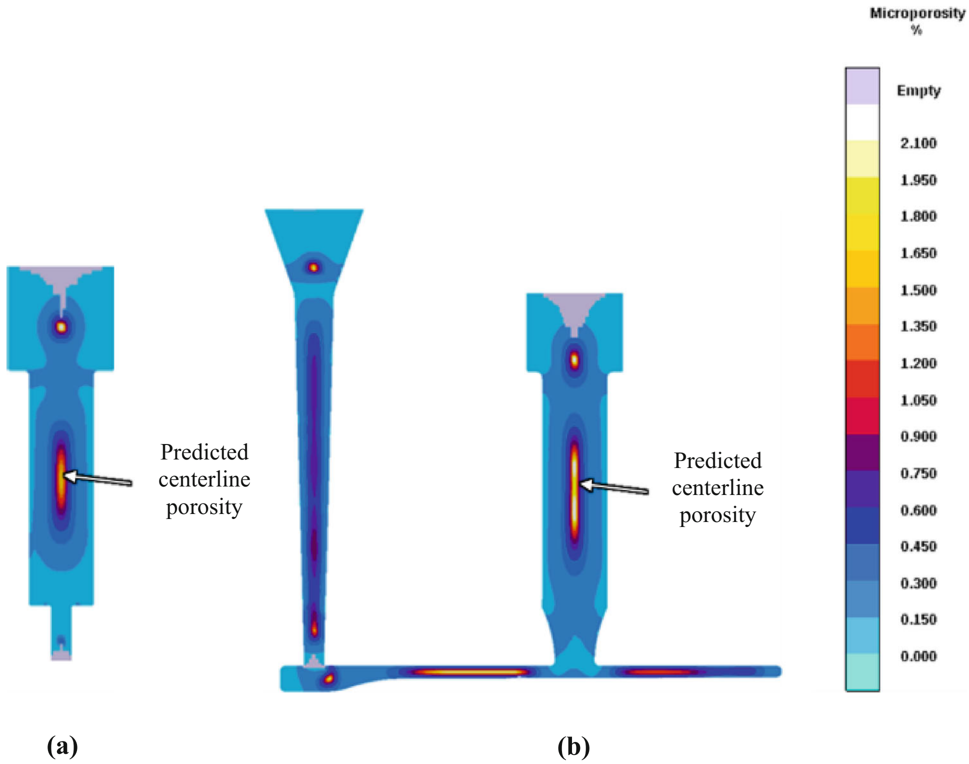

Figure 6. Simulated porosity results for (a) the counter-gravity cylinder and (b) gravity-poured cylinder. Pressurization during solidification was not simulated.

has solidified, the vacuum pressure is released by turning the three-way valve #1 to atmosphere, and any liquid steel in the snout returns to the furnace.

After filling, the upper chamber is moved onto the lower chamber and the two chambers are sealed together. The three-way ball valve #1 is set to the main line, while the three-way ball valve #2 is set to the nitrogen pressurization line, pressurizing the entire system, as illustrated in Figure 4b. Nitrogen was the only gas considered for this study. The only purpose of the gas was to apply pressure to the top of the riser. Therefore, other unreactive gases such as argon or helium could be substituted. Exothermic hot topping is placed at the top of the riser prior to filling, shown in Figure 3. This keeps the metal liquid at the top of casting's riser, while a shell forms around the rest of the casting. This causes the pressure to act only on the top of the riser, forcing the liquid metal further into the casting to feed the solidification shrinkage. While the process described here uses an exothermic powder for the riser topping, any insulating or exothermic material that enables pressure communication with liquid in the riser should work. The system remains under pressure until the casting fully solidifies.

The filling and solidification stages required that an airtight vessel contains the mold and casting. The upper chamber shown in Figure 2a was designed with CAD software and constructed in-house. The chamber, which was constructed using 3.18-mm-thick welded steel plates, was designed with an air inlet port, a connecting port for a pressure transducer, a wire feed-through if thermocouple measurements were desired, lift hooks to transport the chamber during the experiment via pneumatic hoist, and reinforcing angle iron brackets, which provided additional wall stiffness during the pressurization stage. A fused silica ceramic snout protruded from the underside of the chamber, and the thermal properties of the ceramic snout allowed it to be lowered directly into the furnace of molten steel. A silicon gasket and three steel disks sealed and compressed the gasket to the bottom of the chamber, as shown in Figure 2b.

A silica sand mold with furan binder was attached directly to the top of the ceramic snout. Mold glue and steel wire were used to secure the mold to the snout and prevent the mold from lifting off during filling. The mold included air vents to carry excess gas from the burning binder away from the casting surface. A steel chill was placed around the inlet of the mold to accelerate solidification at that location, allowing the vacuum pressure to be released sooner. The space in the upper chamber surrounding the mold was filled with loose sand to stabilize the mold and protect the chamber walls from liquid metal overflowing the top of the mold. During filling, a refractory blanket was secured to the underside of the upper chamber to protect it from heat radiating from the furnace.

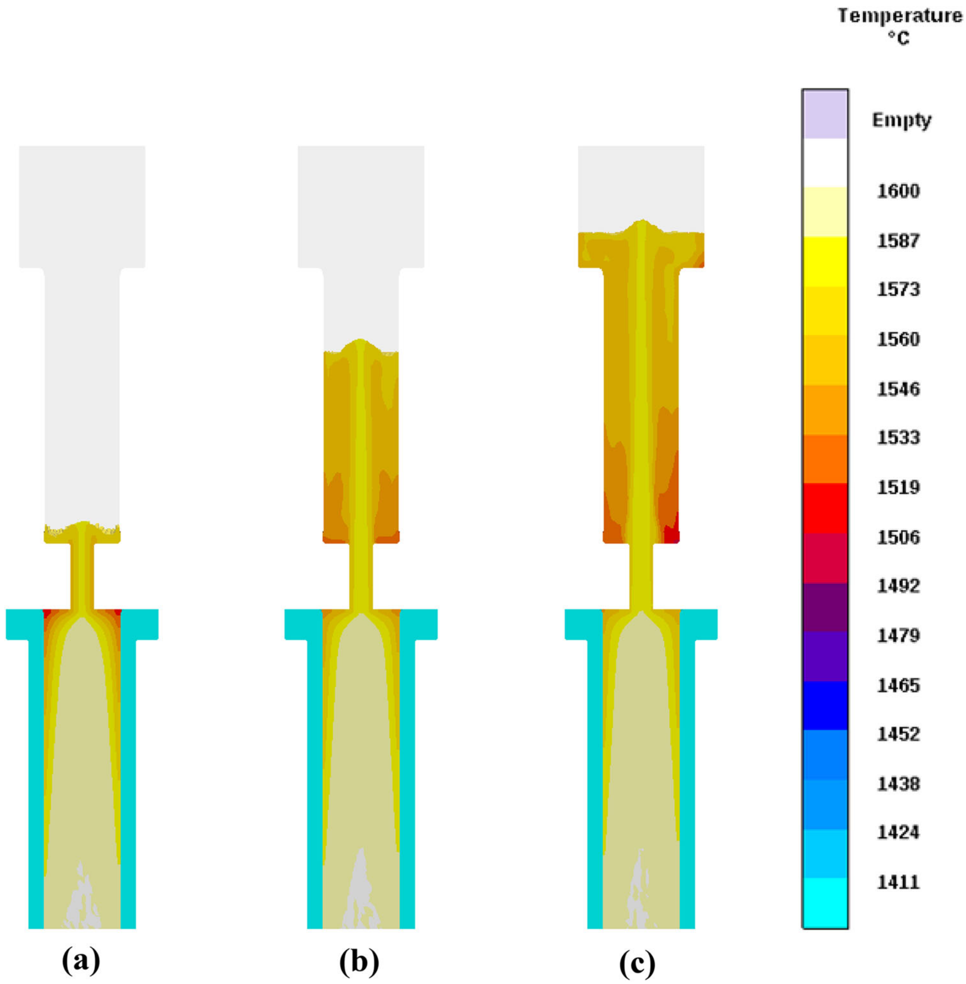

Figure 7. Predicted temperatures during counter-gravity filling at (a) 6.0 (b) 9.0, and (c) 12.0 s. A fill time of 16 s is relatively quick while still avoiding fountaining and air entrainment.

Table 1. Chemical Composition of the CGPS Castings (wt%)

Alloy	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	V
A216	0.308	0.586	0.684	0.016	0.015	0.161	0.028	0.049	0.085	0.073	0.015

As part of experimental trials used in the process development, it was found that the solidifying steel shrinks away from the mold wall, which creates a pathway for gas to escape around the casting and out the bottom of the upper chamber during the pressurization stage. To counter this, the lower chamber was used to provide a better seal during pressurization. The lower chamber was constructed in a similar manner to the upper chamber with angle iron welded on to provide strength during the pressurization stage. The upper and lower chambers were sealed together with latches and a silicon gasket, which is shown in Figure 2b. The flange surfaces where the two chambers join were precision-machined to form a reliable seal.

As shown in Figure 5a, the casting designed for the CGPS experiment was a 64 mm diameter by 229 mm tall cylindrical bar casting with a 105-mm-diameter riser above it. The casting design and dimensions were determined using solidification modeling[10] so that detectable shrinkage porosity would form in a casting unpressurized during solidification. A traditional gravity-poured casting was developed, as shown in Figure 5b, which included the same cylindrical bar casting as the CGPS mold. The gravity-poured casting rigging included a runner and sprue. The runner system of the control castings was designed so that the bar filled as smoothly as possible for a gravity-poured casting. The riser of the CGPS casting was a slightly larger

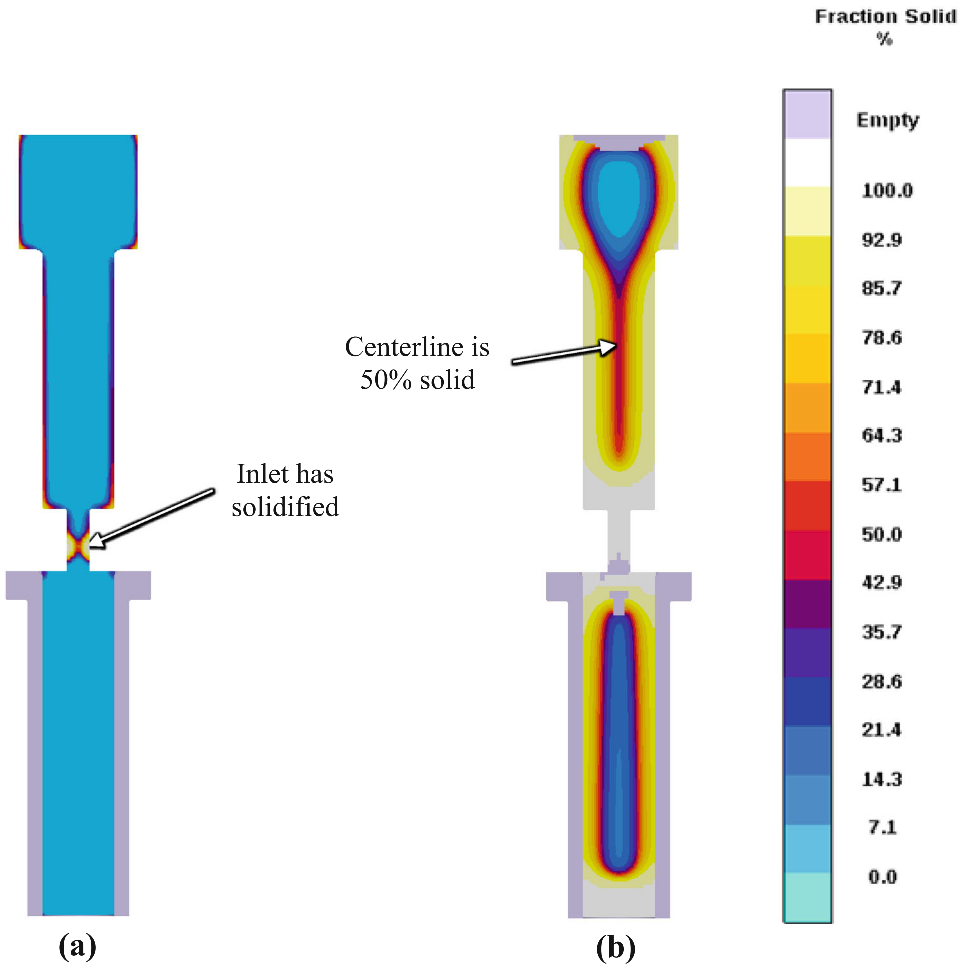

Figure 8. Predicted fraction solid at key events during solidification. (a) 36 s after the start of filling the inlet freezes, and at (b) 217 s the centerline of the casting is 50% solid.

design than the control casting to compensate for the possibility of the riser not filling completely during the counter-gravity filling process. Porosity predictions from casting simulations in Figure 6 show that both castings exhibited centerline porosity without the use of pressurization during solidification. Without the need for a sprue or runner, the casting yield was 47% for the CGPS casting, which was 15% higher than the conventional gravity-poured sand casting's yield at 32%. These values assumed that both castings are filled completely.

Experimental Procedure

The pressure schedule used during the experiment was determined using simulation results and Pascal's Law. Casting simulations[10] of filling and solidification were performed using the geometry designed for both the CGPS process and the gravity-poured control casting. Through an iterative process of simulating the counter-gravity filling of the CGPS bar, a fill time of 16 s was found to minimize fill time while ensuring the mold filled without molten metal jetting through the inlet, which is shown in Figure 7. Based on this fill time, a vacuum pressure time curve was calculated so that the pressure during the counter-gravity filling decreased linearly from atmospheric pressure to the holding pressure. This pressure would retain the liquid steel to a height within 25.4 mm below the top of the riser until the casting inlet had solidified. This height was chosen to reduce the risk of the mold overfilling.

The holding pressure was calculated using Pascal's Law $\Delta P = \rho g(\Delta h)$, where ΔP is the pressure difference needed to hold liquid steel at a height of Δh above the melt level in the furnace, ρ is the density of liquid steel, and g is the acceleration due to gravity, 9.81 m/s^2. Jimbo and Cramb[11] determined the density of liquid steel as a function of carbon content and temperature. Based on the steel's chemistry, given in Table 1, for the metal in the furnace before casting, and simulated temperature data, the calculated liquid steel density range was 7037–7104 kg/m^3. This range represents the density of the steel from an initial filling temperature of 1600 °C until the inlet solidified, at which juncture the average casting temperature is 1517 °C.

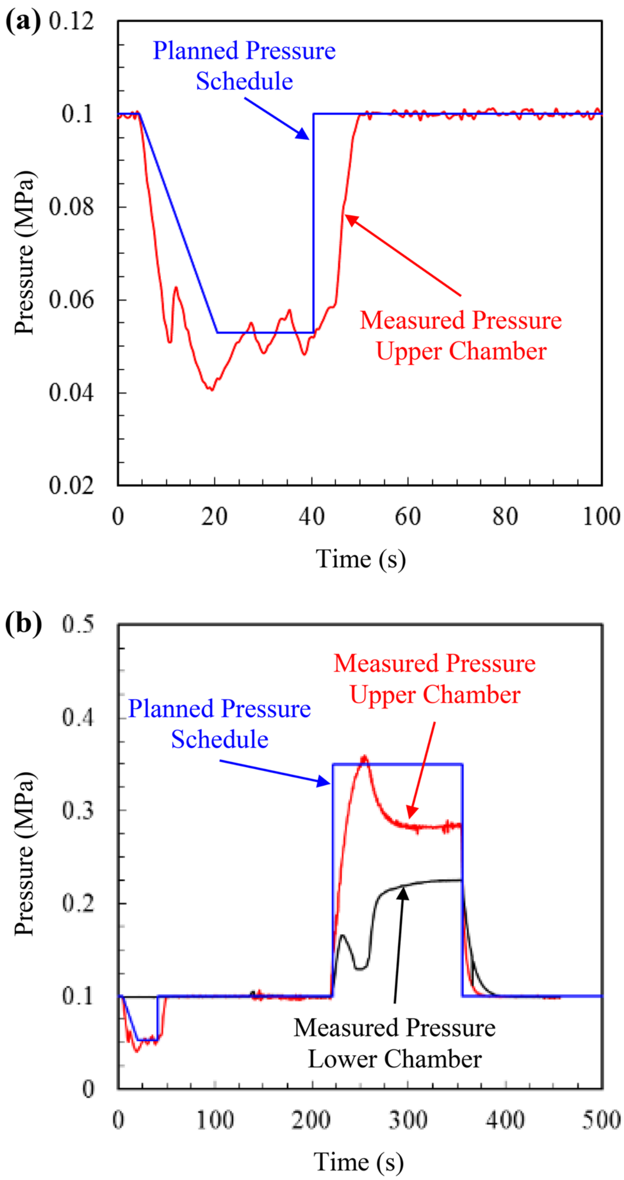

Figure 9. Planned pressure schedule and measured history of pressure of the system during (a) the initial pressure drop and filling of the mold and (b) the entire pressure history of the experiment.

Δh was calculated by subtracting h_f from h_c. As shown in Figure 4a, h_c is the height from the bottom of the snout to within 25.4 mm below the top of the riser, and h_f is the height from the bottom of the snout to the top of the melt in the furnace after the casting has been filled. With the other parameters known, a range of ΔP was calculated. Subtracting ΔP from atmospheric pressure, 0.1013 MPa, resulted in a target holding pressure of 0.0531 $\pm$ 0.0011 MPa.

Solidification simulations were used to predict important events during the casting process. The first key event was the time required for the inlet to solidify; at this time, the vacuum can be released and the upper chamber moved away from the furnace and onto the lower chamber. Simulated solid fraction contours shown in Figure 8a revealed that after 36 s the inlet would have solidified. The second key event during the process was the time to begin pressurization. Pressurizing the casting during low solid fractions would have little effect on the melt, as centerline porosity has yet to form. A reasonable time to start pressurization is when the centerline of the casting first reaches a solid fraction of 0.5 and to continue pressurization until the bar is completely solid. Solid fraction contours in Figure 8b showed that the centerline of the casting achieves a solid fraction of 0.5 at 217 s. The casting is completely solid at 350 s after the start of filling. The system designed for the study was limited a maximum pressure of 0.35 MPa, above which the sealing mechanisms began to fail. Based on the knowledge gained from the simulation, the pressure schedule shown in Figure 9 was constructed for the pressure within the upper chamber, during both the filling and solidification phases of the process.

After a pressure schedule had been determined, furan-bonded silica sand molds for the CGPS process and gravity-poured control castings were created in preparation for the experiment. No mold wash or coatings were used. To test the casting process, one CGPS sand mold was cast using grade ASTM A216 WCB steel. It is a low-alloy steel with chemistry cast given in Table 1. Two gravity-poured control sand molds were cast in separate heats using the same steel. The melt temperature measured immediately before the ceramic snout was lowered into the furnace was 1625 °C. The temperature measured in the ladle before filling the gravity-poured castings was 1615 °C for the first and 1602 °C for the second mold, respectively. All three temperatures were at least 100 °C above the liquidus temperature of WCB steel. Temperatures were not measured during filling or solidification for any of the castings. Hot topping was placed on top of the risers of the gravity-poured control castings after filling them. The CGPS experiment was carried out using the procedure described above (with references to Figure 10), and the results were analyzed to determine the effectiveness of the casting method. Following the experiment, all three experimental castings were examined for centerline porosity using radiographic inspection and dye penetrant tests.

Results and Discussion

The measured pressure data in Figure 9 from the upper and lower chamber are compared to the planned pressure schedule. The vacuum pressure controlled by the regulator depends on the vacuum pressure of the accumulator tank. During the experiment, the pressure within the accumulator tank was lower than that used during testing and presetting of the regulator's vacuum pressure level. This led to the initial pressure drop during the filling stage reaching a

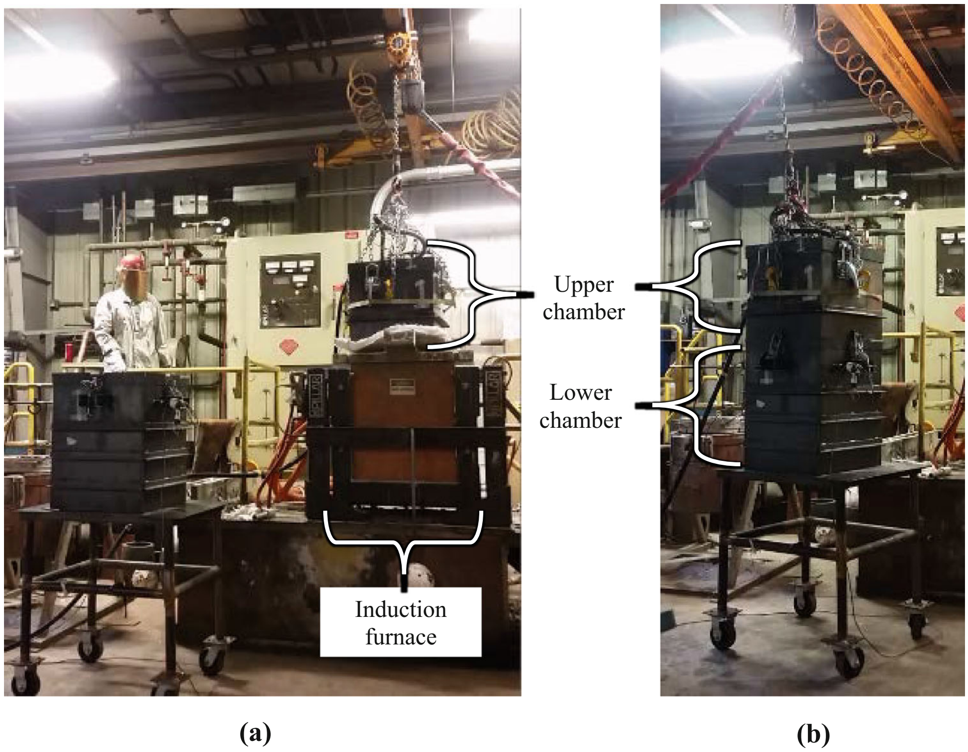

Figure 10. Photographs of (a) the upper chamber positioned over the furnace during the counter-gravity filling process and (b) the upper chamber sealed to the lower chamber during the pressurization process.

Figure 11. Photograph of the sectioned riser from the CGPS casting.

pressure of 0.054 MPa in 5.5 s, which was faster than the intended 16 s filling time determined from simulations. In order to compensate for the rapid pressure drop, the regulator was manually controlled during the experiment to maintain the target vacuum pressure. This led to pressure fluctuations, as shown in Figure 9a. At lower pressures during the fluctuations, the melt reached the top of the mold, and then, at higher pressures the melt receded leaving behind the thin shell of metal at the top of the riser, as shown in Figure 11. The vacuum was released 40 s after the start of filling, a few seconds after the casting inlet was predicted to freeze. It was desired to fill the casting to within 25.4 mm from the top of the riser, which would result in a riser height of at least 75.6 mm. The final height of the CGPS riser was 73.9 mm, 2.2% lower than the target height. This height was measured from the inner edge of the top of the riser to the base of the riser, as described in Figure 11.

When the inlet had solidified, the upper chamber was moved and sealed to the lower chamber. The entire system was pressurized 220 s after the start of filling, as shown in Figure 9b, which was approximately the time the centerline of the casting was predicted to be at a solid fraction of 0.5. Initially, the pressure in the upper chamber reached the maximum pressure of 0.35 MPa, but due to leaks in the system, the pressure dropped until holding steady at 0.28 MPa for the remainder of the experiment. The increase in pressure of the lower chamber, observed in Figure 9b, occurred due to a pathway that formed between the casting and mold wall, which allowed gas to flow from the upper chamber to the lower chamber. Note the inverse behavior and correspondence in time between the pressure curves of the upper and lower chambers in Figure 9b.

The radiographs shown in Figure 12 were taken of the CGPS and control castings to ascertain if the pressurization process during solidification succeeded in reducing the centerline porosity. The radiograph of the CGPS casting, shown in Figure 12a, did not contain the visible centerline

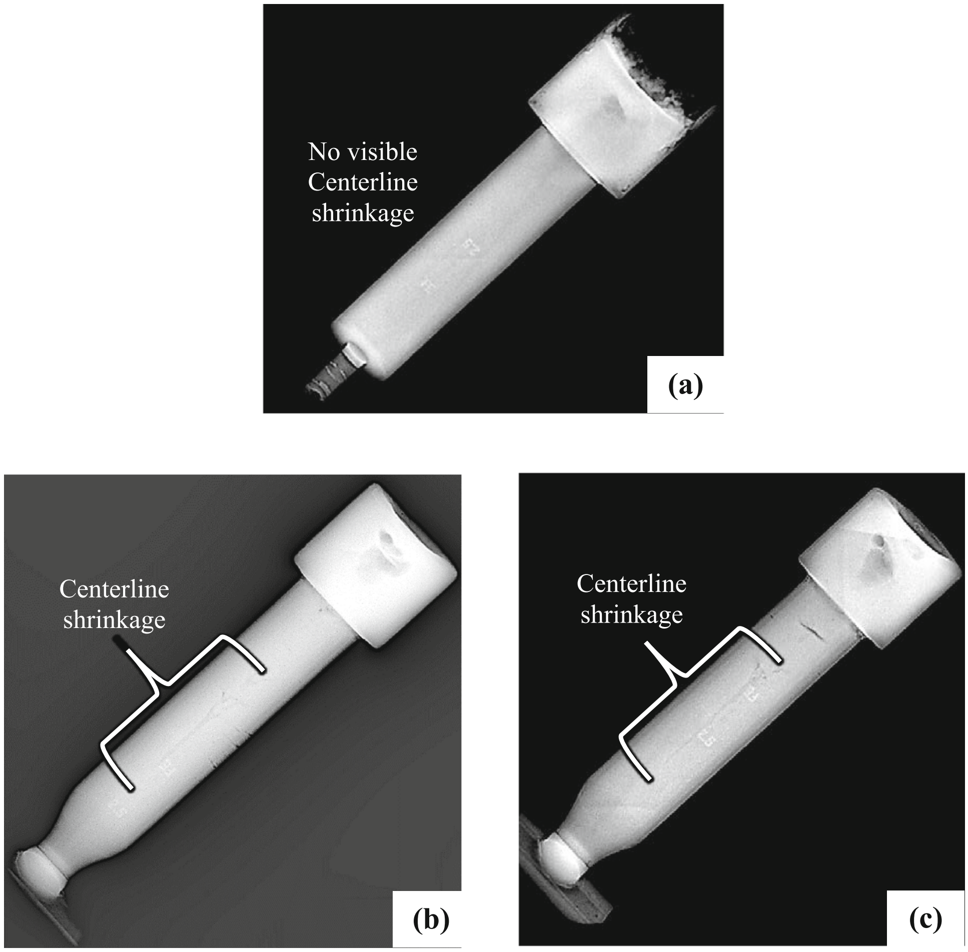

Figure 12. Radiographic images of (a) the CGPS casting, (b) the first gravity-poured casting, and (c) second gravity-poured casting.

porosity that was present in both of the control/unpressurized castings, shown in Figure 12b, c. The centerline porosity in the control castings' radiographs was in good agreement with the predicted porosity from Figure 6. This led to the conclusion that if the CGPS casting was not pressurized, it would have also possessed the shrinkage porosity present in the control castings. The CGPS and one gravity-poured casting were cut through the vertical midplane. A dye penetrant test was performed on the cut-face surface of each casting, shown in Figure 13. The test showed that the CGPS casting possessed none of the centerline shrinkage that was present in the gravity-poured casting. Both the radiographic images and dye penetrant tests indicated that the CGPS process has the potential to eliminate centerline porosity that would otherwise be present in a gravity-poured casting.

Conclusion

A process for casting steel in a sand mold was developed by combining counter-gravity filling with pressurization during solidification. The CGPS system and process were designed using CAD modeling and casting simulations. An experimental trial was performed using the process to cast a cylindrical bar in WCB steel. Simulations showed the casting would contain centerline porosity without the use of pressurization. The CGPS process cast bar was filled with vacuum pressure and was pressurized during solidification to 0.28 MPa. Two unpressurized gravity-poured bars were cast in the same steel alloy, in different heats than the CGPS casting. These unpressurized castings serve as control cases for comparing porosity formed in "traditionally" and CGPS cast bars. Radiographic and dye penetrant inspections of the CGPS casting were compared to the gravity-poured castings. No centerline porosity was visible in the radiographic or dye penetrant images of the CGPS casting, while in contrast, centerline porosity was evident in the gravity-poured castings.

While these initial results using the CGPS process are promising, future work would include additional casting experiments and trials. Future investigations should examine larger castings with more complex geometries, which are difficult to fill without air entrainment and inclusion generation. The capability of counter-gravity

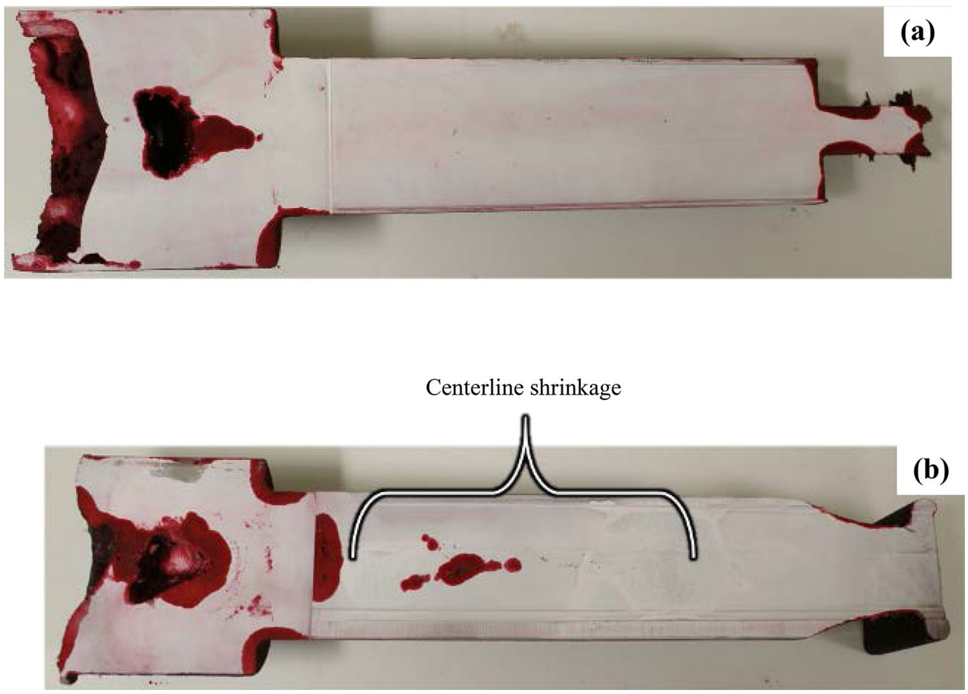

Figure 13. Dye penetrant test results from the (a) CGPS casting and (b) the second gravity-poured casting.

filling to reduce oxide inclusions in steel sand castings would be demonstrated in follow-on work by measurements and comparisons of oxide inclusion levels between CGPS castings, counter-gravity filled castings produced without pressurization, and gravity-poured castings.

Acknowledgments

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