

Translating Water Spray Cooling of a Steel Bar Sand Casting

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Abstract

Ablation casting is a recently introduced process in which the sand mold is ablated, i.e., washed away, from the casting during solidification. The method uses a water-soluble binder and translation of a water spray to achieve directional solidification. The advantages of the ablation technique over traditional casting methods include enhanced feeding characteristics as well as increased ductility and strength. Until now, the ablation method has been used only with aluminum and magnesium alloys. The present study investigates the potential application of the ablation casting method to steel castings. A preliminary casting experiment was conducted where a water spray was translated over the exposed cope surface of a long steel bar during solidification. The experiment demonstrates that the water spray indeed results in improved feeding and the elimination of visible centerline porosity. Mechanical tests performed on the as-cast steel show an increase in strength but a decrease in ductility. While the ablation technique shows promise for use in steel casting, several issues remain, such as finding a suitable water-soluble binder and controlling the water spray to avoid casting distortions.

I. Introduction

The ablation process, which was recently introduced by Grassi et al. [1], is a new method of casting for aluminum and magnesium alloys. This technique uses a water-soluble binder to create the sand mold, which is subsequently dissolved with a water spray after the casting has partially solidified. As it translates across the mold, the spray ablates, i.e., washes away, the sand and impinges directly on the surface of the solidifying casting. An example of this process is shown in Figure 1; for this mold, only the cope was constructed with a water-soluble binder.

The ablation process has several important advantages over traditional casting methods. As shown by Figure 2, the end of the casting opposite of the riser is sprayed first, which leads to a high cooling rate at that location. Once the end has solidified, the spray is slowly translated towards the riser to directionally solidify the bar. During the translation, a temperature gradient is created between the solidification front and riser to enhance the feeding and minimize centerline porosity. Hence, the ablation method can improve the casting yield by reducing the number of risers needed to achieve a sound casting.

The water spray can also improve the mechanical properties of the casting. Generally, higher cooling rates lead to a finer microstructure and, hence, higher strength. The water spray may also lead to more homogeneous mechanical properties throughout the casting.

According to Weiss et al. [2], the high cooling rates increase the tensile strength, yield strength, and % elongation. Other possible benefits of the ablation process include: improved casting of thin sections, low cost, increased efficiency, and the ability to recycle the sand and water.



Figure 1. Modified ablation casting of a long bar, where only the cope is water-soluble.

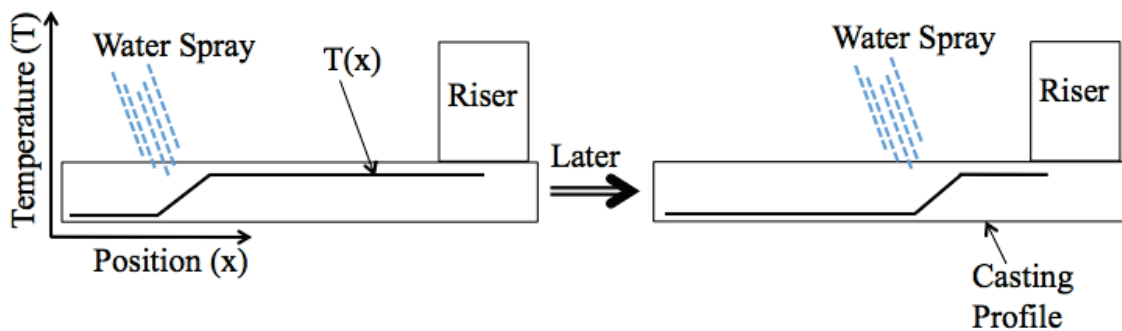


Figure 2. Schematic showing the translation of the temperature gradient along a bar.

Because the method has only been used with aluminum and magnesium alloys, the objective of the present study is to explore the feasibility of the ablation process for steel. A casting experiment is designed, in which two steel bars are produced; one serves as a control, while the other is sprayed with water during solidification. Thermocouples are placed along the length of the bar to measure temperature gradients and cooling rates. After casting, the bars are radiographed and compared to determine the effect of the water spraying on porosity. Additionally, tensile specimens are machined from the castings to investigate the effect of the spray on the mechanical properties of the as-cast steel. Finally, the use of a sodium silicate binder as a water-degradable mold material is investigated.

II. Experimental Procedures

A water spray cooling experiment was conducted at the University of Northern Iowa Metal Casting Center, in which two castings were produced using a plain carbon steel. The steel composition is listed in Table I. The casting, shown in Figure 3, consisted of a 40-inch long, 2-inch square cross-section bar with a riser at one end. One of the castings was exposed to a water spray while the other served as a control. For both castings, a Kalminex 2000 riser sleeve was used to aid in keeping the steel in the riser in a liquid state. To build the molds, silica sand was bonded with a phenolic urethane no-bake (PUNB) binder system. For this preliminary experiment, the mold was not water-soluble. Therefore, in order to spray the casting surface with water, it was necessary to remove the cope at some time during solidification.

Table I. Composition of the plain carbon steel cast in the present experiments.

Composition (wt. %)										
C	Mn	Cr	Mo	Si	P	S	Ni	Al	Cu	V
0.31	0.40	0.22	0.11	0.30	<0.016	0.001	0.02	0.019	0.05	0.03

In order to safely remove the cope and prevent liquid metal from flowing out of the mold, a solid skin must first form around the casting. Therefore, preliminary MAGMASOFT simulations were performed, in which the time to reach 80% solid fraction at a depth of 1 millimeter below the casting surface was calculated. It was assumed that after this time (165 seconds), it would be safe to remove the cope and begin spraying.

Four type B thermocouples were placed along the length of the sprayed bar while two were used in the control bar. The thermocouple positions are shown in Figure 4. The thermocouples measure the temperature at the center of the square cross-section of the bar.

Castings were poured through the open riser, which was then immediately covered with a lid that was constructed with bonded sand. Temperature data was recorded using an IOtech model 3500 Personal DAQ connected to a laptop computer and acquired with DASyLab software at a sampling rate of 2 Hz. At 165 seconds after pouring, the cope was removed and water spraying commenced at the end of the casting opposite of the riser. After the thermocouple near the end of the bar (at the 6-inch location in Figure 4) cooled to a temperature of 1400 °C, the casting was assumed to have locally solidified, at which time the spray was slowly translated towards the next thermocouple; this method was repeated until the water had translated along the length of the bar to the riser. The spray was created using a low-pressure shower garden hose attachment that can be seen in Figures 1 and 5. After spraying, the data sampling rate was reduced to 0.5 Hz until both castings cooled to room temperature. Images from this experiment can be seen in Figure 5.

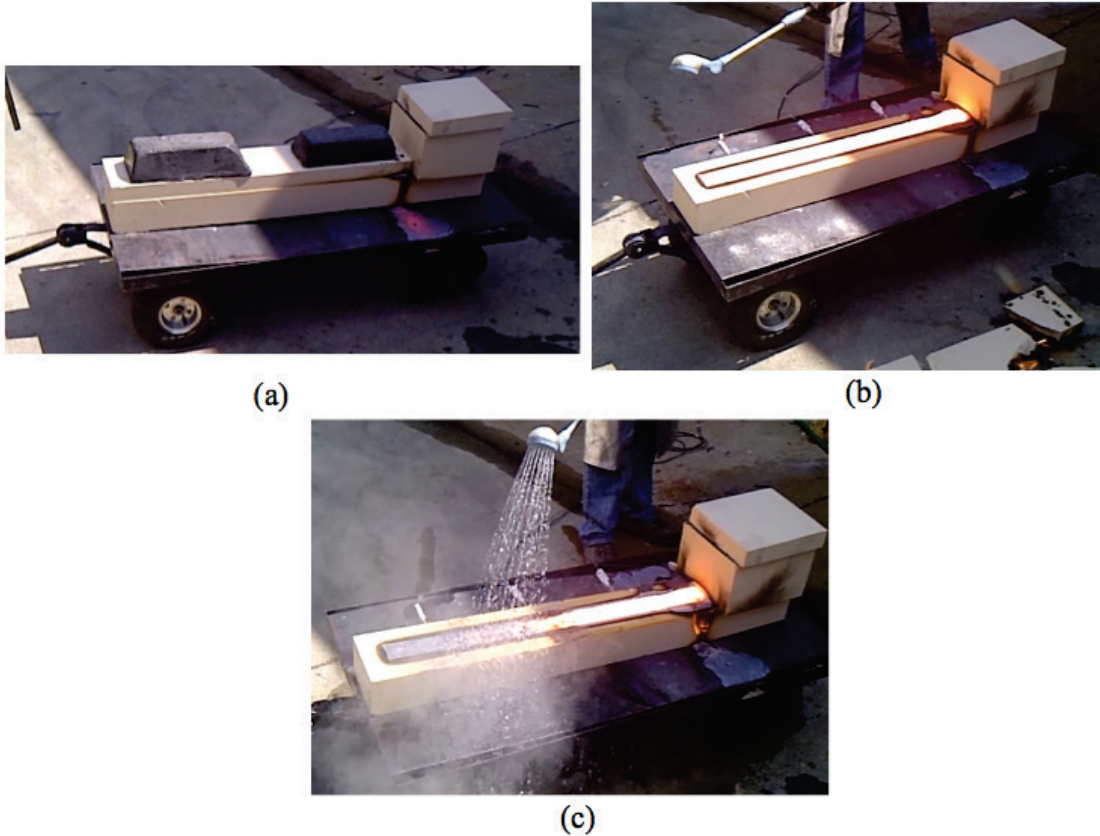


Figure 5. Photographs taken during the ablation process. (a) The casting after pouring, before cope removal. (b) Casting after cope removal, before spraying. (c) Casting during spraying.

After the casting experiments, the bars were taken to Sivyer Steel Corporation in Bettendorf, IA to be radiographed. Following this, tensile test specimens were machined from the bar between the 6-inch and 16-inch thermocouple locations and extracted in such a way as to avoid any effects from centerline shrink. Specimens were flat dog bone shapes with a gauge width and thickness of 0.25 and 0.125 inches, respectively. The gauge length was 3 inches with a 1 inch radius of curvature leading to the grip section of the specimen. Tensile tests were performed at a strain rate of 1×10^{-5} (1/s). Displacement was measured using an extensometer with initial gap of 25.4 mm.

III. Results and Discussion

Temperature results for the sprayed bar are provided in Figure 6; the bottom portion of the plot shows the approximate position of the spray as a function of time (measured from the end of the bar opposite to the riser). The spray translation curve shows that the spraying began at 165 s at the 6-inch thermocouple location and remained stationary until approximately 225 s, after which it was translated instantaneously to the 16-inch thermocouple location. After that, the spray was translated at a (approximately) constant speed until it reached the riser. Unfortunately, several thermocouples failed during the experiment, including both thermocouples in the control and the 36-inch thermocouple

location in the sprayed bar. This left only the 6, 16, and 26-inch thermocouple locations in the sprayed bar to produce temperature data. While limited, this data suggests the spray was successful in creating large thermal gradients along the length of the bar. For example, at 225 s, the thermocouple at the 6-inch location had cooled to 1400 °C while the 16-inch and 26-inch thermocouples were still within 10 °C of the liquidus temperature (1505 °C). This large temperature gradient is likely to have significantly enhanced the feeding and create a sound (i.e., porosity-free) casting. A similar temperature gradient is seen between the 16-inch and 26-inch thermocouple locations at approximately 250 s. These large temperature differences between the thermocouple locations confirm the occurrence of directional solidification. The thermocouple measurements also show that the water spray resulted in large cooling rates. Once the spray reached a particular thermocouple location, it took only 15 to 25 s for the temperature to decrease from a value close to the liquidus temperature (1505 °C) down to 1400 °C. Recall that the thermocouples were located in the center of the cross-section of the bar. This is useful information for planning future experiments.

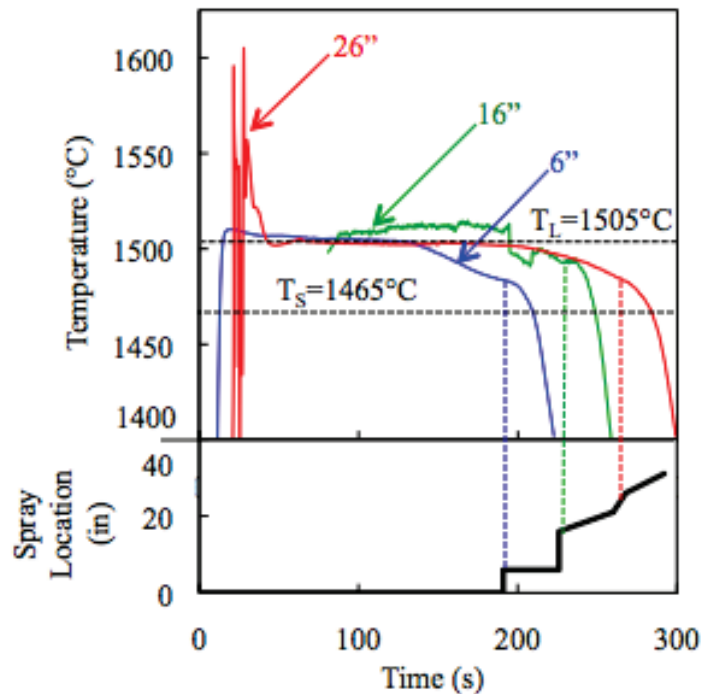


Figure 6. Temperature-time curves for the 6, 16, and 26-inch thermocouple locations. The bottom portion of the chart shows the position of the water spray as a function of time.

The tensile test results of the extracted specimens, which are summarized in Table II, show a significant increase in strength for the sprayed bar but a decrease in ductility. While increases are seen in both the ultimate strength (from approximately 540 MPa to 640 MPa) and yield strength (from 300 MPa to approximately 420 MPa), the ductility drops from 11% to 7%. Defects (such as inclusions) were present in some of the specimens; this is also noted in the table. Significant defects (in Specimen 1 of the sprayed bar and Specimen 4 in the control bar) resulted in drastic decreases in ultimate strength and ductility. The

increased strength for specimens without visible defects is likely due to martensite formation resulting from the high cooling rates. Therefore, it is not presently clear whether there is any benefit from the ablation process with respect to the mechanical properties; the enhanced mechanical properties may solely be the result of a martensitic microstructure. However, these results suggest the possibility of using the ablation technique as a combined casting and heat treatment process, which would increase efficiency of the overall casting production.

Table II. Tensile testing results. The ultimate tensile strength listed for the defective specimens is a breaking strength, as they did not fully reach ultimate strength. The ductility values listed are the strain values at UTS (breaking strain for defective samples).

Specimen	Sprayed Bar		Control Bar				
	1	2	1	2	3	4	5
Yield Strength (MPa)	392	420	300	300	296	358	300
Ultimate Tensile Strength (MPa)	516	643	538	542	498	427	541
Ductility	2.23%	6.96%	12.40%	11.64%	6.34%	1.55%	10.63%
Defect Amount	Significant				Some	Significant	

The radiographs in Figure 7 show that the sprayed bar has no centerline porosity, whereas the control bar has extensive centerline porosity. Hence, the translating water spray indeed improved the feeding of the solidification shrinkage and resulted in a radiographically sound bar. In the present experiment, one riser (located at the end of the bar) was used to feed the entire 40-inch long bar with a 2-inch square cross-section. The riser diameter and height were 3.5 and 6 inches, respectively. Hence, the casting yield, which is defined as the volume of the bar divided by the total volume of the casting, is equal to 73.5%. It is important to note that for the sprayed casting the riser could have been made significantly smaller without compromising the soundness of the bar. Such optimization of the riser size would further increase the casting yield for the sprayed bar. For the control bar, the rules in the SFSA handbook *Feeding and Riser Guidelines for Steel Castings* [3] reveal that at least three risers would be necessary to eliminate centerline porosity and achieve a radiographically sound bar. Assuming the same riser size as in the present experiment, the casting yield would be only 48%. These estimates illustrate the significant improvements in the casting yield that are possible using the ablation process.

In ablation casting, the casting yield is only limited by the distance over which the water spray can be translated without premature solidification of the yet unsprayed portion of the casting. In other words, the casting section adjacent to the riser should not solidify before the water spray has reached it. The translation speed of the spray is only limited by the time it takes to solidify the section being sprayed (about 20 s for the present 2-inch square cross-section). Preliminary estimates show that casting yields in excess of 90% can be achieved.

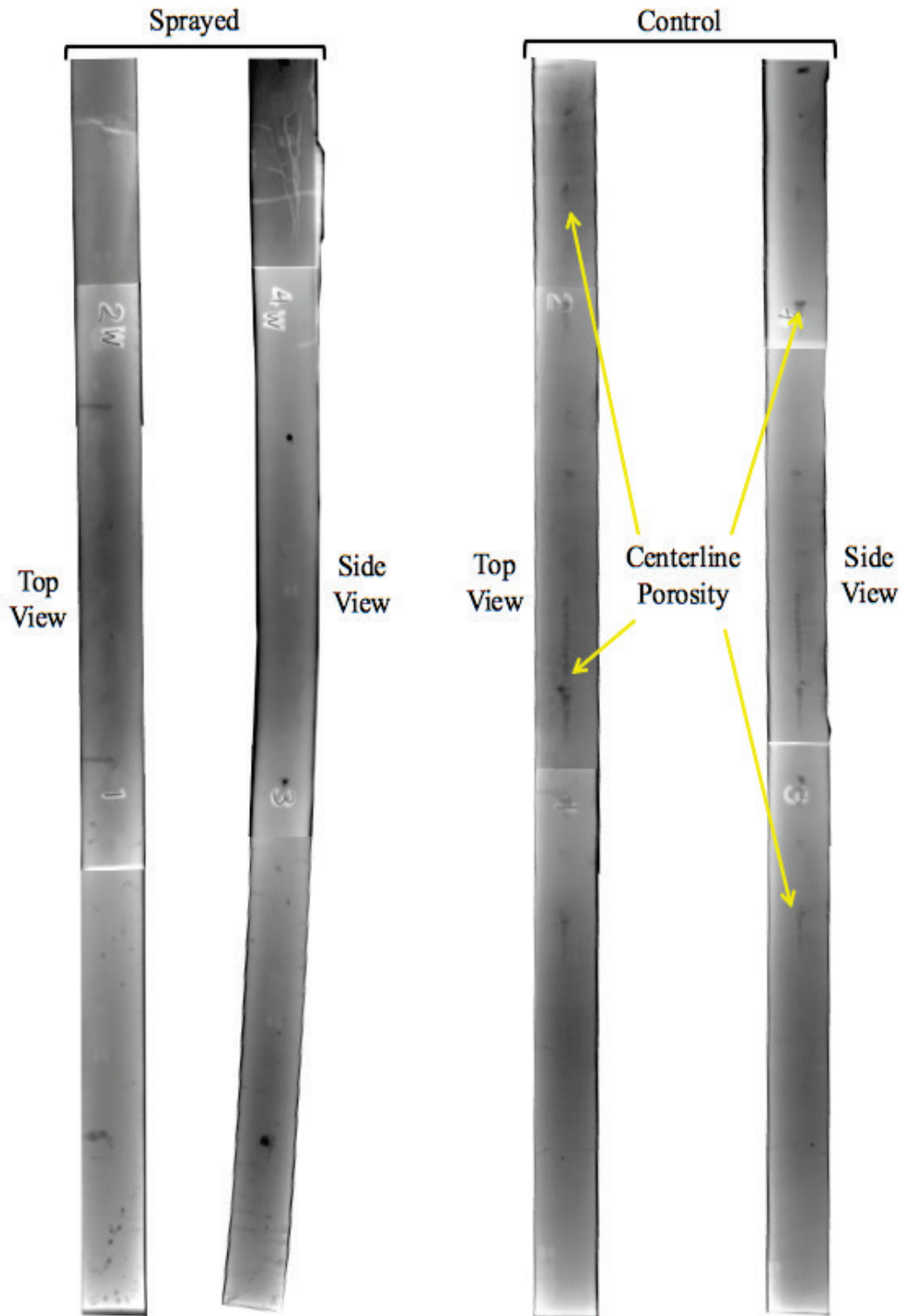


Figure 7. Radiographs of the sprayed and control bars. The riser end of the bar is at the top, which was removed from the radiographs in the interest of space. Neither bar showed signs of porosity directly under the riser.

The side view of the sprayed bar in Figure 7 shows that considerable distortion occurred during cooling to room temperature. This distortion can be attributed to the uneven cooling caused by spraying only the top surface of the bar. The distortion could be minimized by 1) spraying all sides of the bar evenly, or 2) add constraints in the mold.

IV. Investigation of a Sodium Silicate Binder

By definition, the ablation process uses a mold material that can be dissolved by water during solidification. However, the preliminary experiments used a PUNB binder system (that could not be dissolved) to build the mold. Therefore, in order to spray the casting surface, the cope was removed manually. While this experiment provided valuable insight regarding the feasibility of the ablation process for steels, it is obviously not a practical method. Moving forward, water-degradable mold materials must be considered for future experiments. One such possibility is a sodium-silicate binder system. When allowed to cure properly, these binders are extremely strong and durable. However, in the early stages of curing, sodium silicate binders are also water-soluble. Therefore, the possibility for this binding agent to be used in an ablation casting process was explored. Another casting trial was performed, in which 2 bars (with the same geometry as the preliminary experiments) were cast. For this experiment, however, the molds were built using a sodium silicate binder, which consisted of a binder (Carsil) and catalyst (Carset). The binder accounted for 4% of the total mold weight, while the catalyst was based on 2% of the binder weight. Using this binder formulation, a test mold was found to be soluble for at least 1 hour. However, during the experiment, the mold did not properly cure, which resulted in reduced strength and coherency; sections of the mold cracked upon removal from the mold boxes. Due to this difficulty, the drag, riser, and lid sections of the mold (shown in Figure 4) were constructed with a PUNB binder system; only the cope was built using the sodium silicate binder. Unfortunately, the cope also cracked upon removal from the mold boxes and was bonded together with mold glue. After the castings were poured, a water spray ablated the cope (Figure 1), which uncovered another problem with the sodium silicate binder; the binder cured at an accelerated rate after pouring due to the high temperatures of the casting, which resulted in a hard, insoluble mold shell that insulated the casting surface and reduced the ability of the water spray to create a high cooling rate. These difficulties suggest that a sodium silicate binder may not be suitable for use in an ablation process.

V. Conclusions and Future Work

The ablation process is a casting method used for aluminum and magnesium alloys whose advantages over traditional casting methods include enhanced feeding and improved mechanical properties. The present study investigates the feasibility of this technique for steel casting. In the preliminary experiments reported in this study, the cope was removed (rather than ablated) once the casting had formed a solidified shell, after which a translating stream of water was sprayed on the casting surface to induce directional solidification towards the riser. The measured temperatures along the length of the casting show the experiment was successful in creating large temperature gradients. The large temperature gradients resulted in improved feeding during solidification and the elimination of visible centerline porosity. The effect of the ablation process on mechanical properties was also studied; however, the benefits are unclear at this time, as the changes in properties may be

the result of martensite formation due to high cooling rates. A second experiment attempted to use a sodium silicate binder system, which is water-soluble during early stages of curing. However, this system proved to be inadequate, as the sand molds using this binder system experienced strength issues during construction and solubility issues after the metal was cast. Therefore, a water-soluble binder for use in a steel casting must still be created. Also, spraying methods, which include the water delivery system and the translation of the water spray, must also be improved to minimize casting distortions.

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