Development of New Feeding-Distance Rules Using Casting Simulation: Part I. Methodology

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A methodology is developed to relate measured shrinkage porosity levels in steel castings to predictions from casting simulations, in order to determine feeding distances. Low-alloy steel casting trials were conducted to acquire a statistically meaningful set of experimental data for top-risered cast steel sections having various ASTM shrinkage X-ray levels. Simulations of the casting trials were then performed, using casting data recorded at the foundries during the trials. The actual casting soundness resulting from these trials, measured in terms of the ASTM shrinkage X-ray level, is quantitatively compared to the soundness predicted by simulations, measured in terms of a local thermal parameter known as the Niyama criterion. A relationship is shown to exist between the X-ray level and both the minimum Niyama criterion value as well as the area (in the plane of the X-ray) with Niyama values below a threshold value. Once the correlations developed in Part I of this article were established, an extensive set of additional casting simulations was performed to determine the feeding distances for castings with a wide variety of casting parameters. These data were then used to develop a new set of feeding-distance rules, which are given in Part II of this article.

I. INTRODUCTION

THE consequences of a low casting yield are well known in the foundry industry: lower profits due to increased production costs and decreased capacity. Additional melted metal and heats, as well as the increased labor and materials costs required for production, are the primary reasons for the increased costs. Furthermore, it is recognized that a higher casting yield has the side benefit of lowering casting cleaning costs. Essentially, when a foundry achieves the highest possible yield, it can operate at maximum capacity, maximizing its revenues.

Computer simulation of the casting process is becoming an indispensable tool in the effort to achieve increased casting yield. Simulation enables more experimentation with the casting process, since a design can be modified, simulated, and analyzed to determine the effects of the modifications, without having to actually produce the casting. In addition, simulation enables better use of feeding aids such as sleeves and chills, which can sometimes be difficult to apply effectively without numerous trial runs in the foundry. However, computer simulation is applied on a case-by-case basis. Also, to be used effectively, simulation requires expertise and accurate data for numerous process variables. Therefore, in spite of the power of simulation, a recent survey indicates that simulation is used for less than 10 pct of the tonnage of steel castings produced.^[1,2] The same survey indicated that feeding rules (or rule-based software) were used to rig about 80 pct of the tonnage produced. This 80 pct was comprised of 50 pct "rules developed in-house;" 20 pct feeding rules given in the Steel Founders' Society of America (SFSA) handbook, *Risling Steel Castings*; and 10 pct "non-SFSA published rules." Due to the prevalence of rules-based

rigging in the steel casting industry, any attempt to increase casting yield in a general sense must begin with these rules. Furthermore, casting simulation does not provide the initial riser design for a casting, nor does it automatically optimize the risering. Thus, even if simulation is used, feeding rules are useful to develop a reasonable starting point for simulation and to shorten the iterative optimization cycle by providing insight into, for example, the maximum distance between risers.

The first rules governing the riser feeding distance were developed empirically, based on extensive casting trials that were performed in the early 1950s. Most notably, there is the substantial body of experimental work from the Naval Research Laboratory (NRL) by Pellini, Bishop, Myskowski, *et al.* for determining feeding distances^[3-7] and adequate riser dimensions.^[8] In these studies, castings were considered sound if there was no evidence of shrinkage detected by radiography at 1.5 pct sensitivity. Rectangular sections of a thickness of $T = 1.27, 5.08, \text{ and } 10.2 \text{ cm}$ (0.5, 2, and 4 in.), with width-to-thickness ratios of $W/T = 2, 3, 4, \text{ and } 5$, were cast for these studies, as well as bar-shaped cases ("bar": $W/T = 1$) with 15.2 and 20.3 cm (6 and 8 in.) sections. The castings were made of plain-carbon steel of 0.25 to 0.30 wt pct carbon content, with a pouring temperature of approximately 1621 °C. In addition, the SFSA conducted comprehensive casting trials involving about 50 foundries of member companies.^[9] In the SFSA studies, the feeding distance required to cast a section to commercial soundness (better than or equal to ASTM class 2 radiographic testing (RT) soundness at 2 pct sensitivity)^[10,11] was determined for $T = 1.27, 2.54, 5.08, \text{ and } 10.2 \text{ cm}$ (0.5, 1, 2, and 4 in.) plate ("plate": $W/T \geq 3$) and bar ($W/T = 1$) sections. The steel cast in the SFSA studies was reported as a carbon steel of 0.20 to 0.23 wt pct carbon that was cast with pouring temperatures between 1566 °C and 1621 °C, and the mold material used by the foundries was green sand.

Based on the experimental work done by the NRL, the first feeding-distance rules were published by Pellini.^[12] He stated that the maximum feeding distance for a plate is 4.5

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Manuscript submitted December 3, 2001.

T . This value is the sum of a riser contribution of $2T$ and an edge contribution of $2.5T$.

The determination of feeding distances was revisited beginning in 1966 at Case Western Reserve University, Cleveland, Ohio. Under the guidance of Professor J.F. Wallace, computational heat-transfer studies to determine feeding distances were performed by Spiegelberg,^[13,14] Maier,^[15] and Ghun.^[16] Spiegelberg proposed that the solidification gradient could be used as a criterion to determine whether shrinkage porosity would form. The solidification gradient is defined as $g = \Delta f_s / \Delta x$, where f_s is the solid fraction and Δx is the distance measured along the centerline of the casting. The solidification gradient was evaluated near the end of solidification, using the last two nodes in the casting before the mushy zone/solid interface (*i.e.*, using the last two nodes along the centerline with temperatures above the solidus temperature). The solidification gradient was compared to a minimum value ($g_{\min}$), and if $g < g_{\min}$, it was assumed that shrinkage porosity would form (*i.e.*, the feeding distance had been exceeded). The value of $g_{\min}$ was determined numerically, using the NRL casting-trial plates discussed previously. Then, $g_{\min}$ was varied in simulations until the predicted feeding distance (maximum distance with no shrinkage porosity) matched the experimentally determined value. The value that resulted from this process was $g_{\min} = 0.0123 \text{ (cm}^3\text{/cm}^3\text{)/cm}$ ($0.0312 \text{ (in.}^3\text{/in.}^3\text{)/in.}$).

Another method for predicting the onset of shrinkage porosity and, hence, determining the feeding distance, was proposed by Niyama *et al.*^[17] Similar to the concept proposed by Spiegelberg,^[14] Niyama *et al.* suggested a different criterion that could be evaluated and compared to a minimum value, in order to determine the presence or absence of shrinkage porosity. This criterion is known as the Niyama criterion, $Ny = G/\sqrt{\dot{T}}$, where G is the temperature gradient and $\dot{T}$ is the cooling rate. Due to the importance of the Niyama criterion to the present study, this work will be discussed in detail in the next section of this article.

In 1973, the SFSA compiled the experimental results of the 1950s casting trials^[3-9] with the numerical results from Case Western Reserve University^[12-16] into a handbook entitled *Risening Steel Castings*.^[18] This handbook contains charts, nomographs, equations, and procedures useful for risering both low- and high-alloy steel castings, and it is intended to assist foundry engineers in the placement and sizing of risers on steel castings. Although it was published nearly 30 years ago, *Risening Steel Castings* is still utilized in foundry practice today. However, there has been substantial feedback from SFSA members indicating that the current feeding rules published by the SFSA in *Risening Steel Castings* are overly conservative, for both the ASTM shrinkage X-ray level 1 soundness for which they were developed, as well as for higher ASTM RT levels that are commonly stipulated by the customer.^[1] Also, it was noted that these rules do not account for differences in sand mold material, alloy composition, or superheat, all of which are known to affect the distance over which a riser can provide feed metal to a casting section.

Based on this information, it was decided to develop a new set of feeding rules that are less conservative than those in *Risening Steel Castings* and more tailored to particular casting conditions. To accomplish this, an extensive set of casting trials involving low-alloy steel plates was conducted,

in order to acquire a statistically meaningful set of experimental data on the feeding lengths of cast steel sections. These experimental data were then coupled with the results of corresponding numerical simulations in such a way that it was possible to develop correlations between the Niyama criterion and ASTM shrinkage X-ray level. These correlations were then utilized to determine feeding distances for a large additional set of simulations, covering a wide array of plat geometries and casting parameters. The resulting data were then used to develop a new set of guidelines for determining the feeding distances of risers. Part I of this two-part article describes the casting trials, the numerical simulations, and the methodology used to combine the data from this experimental and numerical work to develop the new feeding and risering guidelines. Part II presents these new guidelines for low-alloy steels.

II. OVERVIEW OF THE NIYAMA CRITERION

The Niyama criterion is defined as $G/\sqrt{\dot{T}}$, where G is the temperature gradient in K/mm and $\dot{T}$ is the cooling rate in K/s. Niyama *et al.*^[17] suggest a critical value of

$$G/\sqrt{\dot{T}} = 1.0 \text{ K}^{1/2}\text{min}^{1/2}\text{cm}^{-1} (0.775 \text{ K}^{1/2}\text{s}^{1/2}\text{mm}^{-1}) \quad [1]$$

below which shrinkage defects occur (the latter combination of units is typically used in casting simulation software). For each point in a casting, the Niyama criterion is evaluated at the end of solidification. Niyama *et al.* define the end of solidification as the time when the temperature first reaches or drops below the solidus temperature (T_s). In the present work, the Niyama criterion was evaluated at a higher temperature, equal to the solidus temperature plus 10 pct of the interval between the solidus and liquidus temperatures: $T = T_s + 0.1 (T_l - T_s)$. Evaluating the Niyama criterion at a higher temperature results in a lower critical Niyama value than the one reported by Niyama *et al.*, but the functional correspondence between this parameter and shrinkage porosity remains the same.

The study by Niyama *et al.*^[17] focuses on centerline shrinkage that is formed in areas of shallow temperature gradients. A radiograph containing a severe example of centerline shrinkage is shown in Figure 1. Rules for determining feeding distances in cast sections are concerned with the formation of this type of shrinkage. Niyama *et al.* present experimental results for cast vertical cylinders of different diameters with a top riser and molds made from furan-bonded silica sand. They examined five different steels ranging from regular-carbon/low-alloy steel to high-alloy (*e.g.*, CF8) steel, and they investigated superheats ranging from 50 °C to 100 °C. The castings were tested and sectioned along the vertical centerline. The shrinkage was detected using dye-penetrant (on the cut section), X-ray, and ultrasonic testing.

Niyama *et al.*^[17] used two-dimensional simulations to determine the temperature gradients and cooling rates of the cylinders. In the simulations, the cast-mold heat-transfer coefficient was taken as infinite, and the temperature gradient was evaluated in an approximate way as the maximum local value among eight directions at the end of solidification. The cooling rate was approximated as the difference between the liquidus and solidus temperatures ($T_l - T_s$), divided by the total solidification time (t_f). Because of these approximations, the actual values of the thermal parameters

Fig. 1—Radiograph of a small portion of a plate, illustrating centerline shrinkage (on the left side of the figure) within an otherwise sound region.

computed by Niyama *et al.* should be viewed with caution, especially when comparing them to values from modern three-dimensional casting simulation codes. The key finding of Niyama *et al.* is that the critical temperature gradient (G) at which porosity forms is proportional to $1/\sqrt{t_f}$. Since $\dot{T} = (T_l - T_s)/t_f$, this finding can also be expressed as the usual Niyama criterion, $G/\sqrt{\dot{T}} > \text{const.}$, for the casting to be sound. Niyama *et al.* computed the constant by comparing their numerical and experimental data, which resulted in the critical value listed at the beginning of this section. Another noteworthy finding is that the same critical Niyama value was found to apply to all alloys, superheat values, and casting-section thicknesses, within the ranges studied.

In an appendix, Niyama *et al.*^[17] provide a theoretical justification of the Niyama criterion based on Darcy's law for interdendritic flow. Their analysis shows that the pressure drop is proportional to $(G/\sqrt{\dot{T}})^{-2}$. If the pressure drop exceeds a certain value, porosity will form. While their argument provides validity for the use of the Niyama criterion to predict porosity, it is not directly applicable to centerline shrinkage, as explained subsequently.

Sigworth and Wang^[19] derive a model for centerline shrinkage of the type found in the present casting trials, based on geometric arguments. They argue that "pinching off" of liquid areas along the plate centerline due to uneven solidification causes the shrinkage in plates. These isolated areas solidify without feeding and will exhibit shrinkage, as shown in Figure 2(a). The presence of a gradient in the feeding direction serves to open up a channel by effectively providing a taper to the inner liquid channel, as shown in Figure 2(b). Assuming that feeding occurs as long as the tapered channel has an angle greater than a certain critical angle (θ_c), the critical ratio of the temperature gradient along the plate (G_x) to the one across the mush in a direction perpendicular to the centerline (G_y) is given by $G_x/G_y = \tan \theta_c$. The thermal gradient across the mush is given by $G_y \approx (T_l - T_s)/l$, where l is the thickness of the mush. According

Fig. 2—Illustration of a platelike casting (a) without and (b) with an adequate thermal gradient to prevent formation of shrinkage porosity (adapted from Ref. 19).

to Flemings,^[20] the thickness of the mush grows as $l \sim \sqrt{t}$. Following the derivations of Sigworth and Wang,^[19] the final expression for the critical temperature gradient is then given by

$$G_x = \frac{T_l - T_s}{2\sqrt{\pi k_M}} \sqrt{k_m \rho_m c_m} \tan \theta_c \frac{1}{\sqrt{t_f}} = \frac{A}{\sqrt{t_f}} \quad [2]$$

where k_m , ρ_m , and c_m are the thermal conductivity, density, and specific heat, respectively, of the mold, and k_M is the thermal conductivity of the metal. Substituting appropriate values for the properties and taking measured critical temperature gradients from Pellini's experiments (Pellini used RT to measure shrinkage),^[12] Sigworth and Wang estimate a critical angle for steel plates between 2 and 5 deg, which appears reasonable.

The most important conclusion, however, is that this alternative derivation results in the same functional dependence between the temperature gradient and the solidification time as that found experimentally by Niyama *et al.*^[17] Note that substitution of the cooling rate for the solidification time results in the usual Niyama parameter $G/\sqrt{\dot{T}}$. Niyama *et al.*, as well as casting simulation codes, do not use the thermal gradient G_x along the plate centerline. Therefore, the constant A in the previous equation would be different, and its exact value depends on how the thermal parameters are evaluated.

III. LOW-ALLOY PLATE CASTING TRIALS

As part of the present study, six different foundries cast a total of 203 low-alloy plates with a single top riser, using a general configuration such as the one shown in Figure 3. The plates can be categorized into three groups, based on their cross section: 56 of the plates had a cross section 7.62-cm thick by 15.2-cm wide (3-in. thick by 6-in. wide), 75 plates were 2.54 by 14.0 cm (1 by 5.5 in.), and the remaining 72 plates were 2.54 by 25.4 cm (1 by 10 in.). For brevity, these groups of plates will, hereafter, be referred to by their width-to-thickness (W/T) ratios: $W/T = 2, 5.5$, and

Fig. 3—General configuration and nomenclature for the horizontal plate casting trials.

10, respectively. Several different lengths were cast for each of these groups of plates, with the lengths selected to produce plates ranging from radiographically sound to an ASTM shrinkage X-ray level 5 (very unsound). All of the plates described previously were cast from ASTM 1025 or a similar alloy, in either polyurethane no-bake (PUNB) or green sand molds. Further detail regarding the casting trials is given in publications of preliminary results of this work.^[21,22]

When conducting the casting trials, it was envisioned that the trials would include the normal variations in casting conditions that are possible in foundry practice. These variations would then be considered in the analysis of the results. Therefore, detailed information was collected on the casting process for the trial plates, and all information was recorded in detailed data sheets that were filled out by the participating foundries. The casting parameters that were recorded were the pouring temperature, pouring time, steel chemistry, mold material, actual casting rigging, and mold-box geometry. In addition, each plate cast in these trials was examined by RT using ASTM E94^[23] procedures (E186^[10] for 7.62-cm-thick (3-in.-thick) plates, and E446^[11] for 2.54-cm-thick (1-in.-thick) plates). Based on this examination, an ASTM shrinkage RT level was assigned to each plate.

With regard to the X-ray ratings, it is important to bear in mind that the process of assigning an ASTM RT level to an X-ray (for shrinkage, gas porosity, or inclusions) is far from an exact science. A study of the variability inherent in the current ASTM shrinkage X-ray rating procedure for steel castings has recently been published by the present authors.^[24] The radiographs for most of the $W/T = 2$ plates mentioned previously were used for the study. In all, 128 X-rays were used. Note that 128 X-rays does not imply 128 plates, as some plates had multiple X-rays. These X-rays were sent to four different radiographers to be rated for shrinkage RT level. Two of the radiographers rated the X-rays twice. This provided a total of seven ratings for each X-ray (the six ratings just described, along with the original rating provided by the casting foundry). A statistical analysis was performed on these data, and it was found that the average variability involved in assigning an ASTM shrinkage X-ray level to an X-ray is about ± 1.4 . Furthermore,

the variability for level 2 and level 3 X-rays is about ± 2 .^[24] Several factors that are thought to contribute to this variability are mentioned. They include comparing nonuniform shrinkage patterns on production X-rays (e.g., centerline shrinkage) to the uniform patterns on the ASTM standard radiographs; the requirement in the standards to prorate the size of the area of interest in the production X-ray to the size of the standard; and the arbitrary selection of the size of the area of interest (how much of the radiographically sound region around the defects should be included in this area?).

As a final note regarding the casting trials, it should be mentioned that the experimental results presented in this work differ slightly from preliminary results published in the literature.^[21,22] One source of discrepancy is that some of the original data were eliminated. The $W/T = 2$ plates from one foundry were removed, because the radiographs from this foundry were of poor quality—they were very dark, making defects difficult to detect. The $W/T = 5.5$ plates from another foundry were removed from the data set because inadequate casting data were gathered to accurately simulate these plates. Another source of discrepancy is that the shrinkage X-ray ratings of the plates whose X-rays were used in the X-ray variability study discussed earlier^[24] were adjusted to reflect a consensus shrinkage rating. The average X-ray level among the seven ratings for each X-ray was computed, and this value was rounded to the nearest integer. Finally, due to obvious, large discrepancies between the shrinkage visible on the $W/T = 10$ X-rays and their corresponding original shrinkage ratings, these X-rays were rerated by another radiographer, who rated them all twice. These reratings were more in line with what was visible on the X-rays, so the original ratings were discarded, and the two reratings were averaged and rounded up to determine the shrinkage X-ray levels.

Figure 3 shows the definition of the feeding length (FL) for plates. Another term that will be used frequently in this article is feeding distance (FD). Since they are easily confused, the feeding distance and the feeding length are clearly defined in the context of the present work to avoid confusion.

A. Feeding Distance

The feeding distance is the distance from the riser to the furthest point in the casting over which the riser can provide feed metal *resulting in a radiographically sound casting*. In the case of the SFSA guidelines, soundness is defined as “class I soundness at 2 pct radiographic sensitivity.”^[18]

B. Feeding Length

As given in Figure 3 for the casting-trial cases, the feeding length is the distance from the riser to the furthest point in the casting. It is the length to be fed. It is purely geometrical, and *implies nothing about the soundness of the casting being fed*.

The results of the casting trials are given in Figures 4 through 6, which plot the feeding lengths of the $W/T = 2$, 5.5, and 10 plates, respectively, against the resulting ASTM shrinkage X-ray level for each corresponding plate. The different hollow symbols indicate plates cast by different

Fig. 4—Casting trial results for the $W/T = 2$ [7.62 cm by 15.2 cm (3 in. T by 6 in. W)] plates: soundness vs feeding length.

Fig. 5—Casting trial results for the $W/T = 5.5$ [2.54 cm by 14.0 cm (1 in. T by 5.5 in. W)] plates: soundness vs feeding length.

Fig. 6—Casting trial results for the $W/T = 10$ [2.54 cm by 25.4 cm (1 in. T by 10 in. W)] plates: soundness vs feeding length.

foundries. When a number appears next to a symbol (or group of overlapping symbols), this indicates the number of plates of that feeding length with the same X-ray level. The shrinkage X-ray levels in these figures range from 0 to 5, where level 0 indicates that the plate was radiographically sound (*i.e.*, absolutely no indications visible on the X-ray).

While level 0 is not a standard ASTM X-ray level, it is used in this study because it provides additional information. Also shown in these figures are the mean X-ray level for each value of feeding length, as well as error bars indicating one standard deviation. The mean values and error bars are not intended to provide meaningful statistical data (the number of plates at each feeding length is generally small, and X-ray levels are quantized rather than continuous data), but, rather, they are provided to more clearly indicate the trends in the data.

Figures 4 through 6 show that, as the plate length increases, the average shrinkage X-ray level tends to increase as well. An interesting feature of the casting-trial results visible in these figures is the spread of X-ray levels for a given feeding length. Notice that there are several instances in Figures 4 through 6 where the X-ray levels at a given feeding length vary from level 0 to level 4, or from level 1 to level 5. This is particularly evident for the longer feeding lengths. This scatter is partially due to the variability in the casting process. The exact steel composition, pouring temperature, pouring time, mold material, *etc.*, varied from foundry to foundry. The effect of such differences in the production setting is visible in the results shown in Figures 4 through 6; notice that the variation in X-ray level at a given feeding length for any one foundry is generally smaller than the total variation at that feeding length. Some casting parameters (*e.g.*, pouring temperature) even varied to some degree within a single foundry. Another factor contributing to the scatter in X-ray level at a given feeding length is the variability inherent in assigning X-ray levels to an X-ray (about ± 1.4 X-ray levels, on average), as was discussed earlier in this section. A final cause of the scatter is the presence of gas porosity (of a spherical nature, and, thus, not considered in the shrinkage rating) in some of these plates.

IV. SIMULATION OF CASTING TRIALS

Based on the information given on the casting-trial data sheets for the plates, simulations were performed for each plate for which unique casting data were available, using the commercial simulation software package MAGMASOFT.*

*Although MAGMASOFT^[27] was used in this work to simulate the casting trials, a number of simulation packages are available, and most of them are capable of calculating the Niyama criterion. In fact, the authors recently performed a comparison between MAGMASOFT and AFSolid^[28] and determined that the Niyama values calculated by these two packages for the same casting conditions are similar, provided that one takes care to ensure that the Niyama values are calculated in the same manner (*e.g.*, evaluated at the same temperature) and that the values are converted to the same units.^[29]

By using this detailed casting information as input for the simulations, it was possible to account for the variability due to differences in casting parameters from foundry to foundry (and from plate to plate). Simulation of the filling process was included, to model the flow of the melt through the gating and into the castings, as well as the cooling of the metal which occurs during this process. Steel chemistry was taken into account in these detailed simulations, because it is known to have an effect on the Niyama criterion. The effects of chemistry on the thermophysical properties of the steel, including the liquidus and solidus temperatures (T_l and T_s , respectively), were computed using the interdendritic solidification computer software (IDS) developed by

Fig. 7—Niyama value distribution in a 7.62 cm by 15.2 cm by 68.6 cm (3 in. T by 6 in. W by 27 in. L) plate: (a) top view of central-thickness cross section; and (b) side view of central-width cross section.

Miettinen *et al.*^[25,26] The variation with steel chemistry of the Niyama-criterion results is due primarily to changes in the liquidus and solidus temperatures for slightly different chemistries. These changes affect the temperature at which the temperature gradient and cooling rate are computed. The values computed with IDS were compared to those for the appropriate steel from the MAGMASOFT property database. In most cases, they were found to agree quite well, but when the differences were large enough to affect the results, the IDS property values were used.

The simulations of the plate casting trials provided the distribution of the Niyama criterion throughout the castings. An example of the Niyama-value distribution in a typical plate is shown in Figure 7. This is a simulation of a 7.62 by 15.2 by 68.6 cm (3 in. by 6 by 27 in.) plate (width by thickness by length, respectively), which is long enough to easily exceed the feeding distance for the riser. In the casting trials, centerline shrinkage, of the type shown in Figure 1, was commonly found in plates with these dimensions. Notice that, in both the top view (Figure 7(a)) and the side view (Figure 7(b)), the lowest Niyama values (*i.e.*, the darkest cells) are confined to the center of the plate. The region with the lowest Niyama values corresponds very closely to the region where centerline shrinkage occurs. This is further evidence of the ability of the Niyama criterion to detect centerline shrinkage, as well as more-general shrinkage porosity.

For each simulated plate, the minimum value of the Niyama criterion in the central-thickness cross section (*i.e.*, the plane one would see in a typical X-ray of the plate, Figure 7(a)) was determined for each simulation. In addition, the total area in that same cross section with Niyama criterion values below some critical value was also recorded for each simulation. It is important to note that care must be taken when extracting Niyama values from simulation results. For example, in the present study, it was necessary to turn off the postprocessor's interpolation function (which is set "on" by default in MAGMASOFT) in order to determine the correct Niyama values for each metal cell of interest.

Fig. 8—Simulation results for the $W/T = 2$ [7.62 cm by 15.2 cm (3 in. T by 6 in. W)] plates: minimum Niyama value vs feeding length.

Figure 8 plots the minimum Niyama values of the $W/T = 2$ plates against the feeding length of each plate. There is a very obvious trend of decreasing minimum Niyama values as the feeding length increases (and, hence, plate soundness decreases). Analogous plots for the $W/T = 5.5$ and 10 plates look very similar to Figure 8; for this reason, they are not presented here.

Computational results such as those in Figure 8 can be combined with the experimental results shown in Figures 4 through 6 by eliminating the feeding length from these figures and simply plotting the ASTM shrinkage X-ray level determined for each plate vs the minimum Niyama value resulting from the simulation of that plate. In other words, one can plot the measured soundness, in terms of shrinkage X-ray level, against the predicted soundness, in terms of minimum Niyama value. This is shown in Figure 9, which includes all 203 low-alloy plates ($W/T = 2, 5.5$, and 10) described in the previous section. The first noteworthy feature of this figure is a definite tendency toward lower and lower minimum Niyama values as the X-ray level increases. This trend is highlighted in the plot inset in the upper-right corner of Figure 9, which shows the mean value of $N_{y_{min}}$ for plates having X-ray levels from level 1 to 4. The mean values for each X-ray level are shown with bars indicating the size of the range, from a -1 to 1 standard deviation from the mean. This is an indication of the scatter of the values for plates with a given X-ray level. No mean minimum Niyama values are given for levels 0 or 5, because the mean value for level 5 plates could be made almost arbitrarily small by casting a large number of very long plates, and the mean value for level 0 plates could similarly be made almost arbitrarily large by casting a large number of short plates.

Fig. 9—ASTM shrinkage X-ray level vs minimum Niyama criterion value for the $W/T = 2, 5.5$, and 10 plates.

Note that the minimum Niyama value asymptotes to zero as the X-ray level increases to level 5, and that the scatter in $Ny_{\min}$ tends to decrease as the X-ray level increases.

It is also apparent from Figure 9 that a plate with a relatively large value of $Ny_{\min}$ will have a low X-ray level. Note that almost all of the plates with a minimum Niyama value greater than 0.2 are level 1 or better, and most of the plates with $Ny_{\min} > 0.1$ are level 1 or better. The plates with $Ny_{\min} > 0.1$ that have X-ray levels higher than level 1 are considered outliers; they are the result of (1) the previously mentioned scatter in the experimental data that could not be accounted for in the simulations, and (2) differences between the actual casting conditions and the values that were recorded. As an example of the latter, if the recorded superheat was higher than the actual superheat, the simulation would result in a plate more sound (hence, with a larger $Ny_{\min}$) than was produced in the trials. It is evident that there is a transition, as the Niyama value decreases to somewhere around 0.1 to 0.2 , from radiographically sound plates to unsound plates. For the present study, it was desirable to define some threshold value to denote this transition. The value chosen as the threshold is $Ny_{\min} = 0.1$. This value will be justified shortly.

While it is true that a relatively large Niyama value indicates that a plate will probably have a low X-ray level, the converse is not true: a small value of $Ny_{\min}$ does not necessarily imply that the corresponding plate will have a high X-ray level. This is evident from the 27 plates in the lower-left corner of Figure 9 that are level 1 or better and, yet, have $Ny_{\min} < 0.05$. Although this may appear troubling at first glance, it can be explained by considering Figure 9 in conjunction with Figures 10 through 12. Figure 10 plots the shrinkage X-ray level of the $W/T = 2$ plates against the area of these plates with Niyama-criterion values below the threshold value of 0.1 , measured from the corresponding plate simulations (Figure 7(a)). Figures 11 and 12 are analogous plots for the $W/T = 5.5$ and 10 plates, respectively. Figures 10 through 12 include the values for each individual plate (numbers next to symbols indicate multiple plates with the same value), as well as the mean area for all of the plates at each X-ray level, with a standard deviation of ± 1 . As in Figure 9, no mean values are given for levels 0 or 5 in these figures, because the mean areas for these levels are rather arbitrary. An area of zero indicates that the minimum Niyama

Fig. 10—Casting soundness vs area of cells below Niyama criterion threshold value of $0.1 (K s)^{1/2}/mm$, for the $W/T = 2$ plates.

Fig. 11—Casting soundness vs area of cells below Niyama criterion threshold value of $0.1 (K s)^{1/2}/mm$, for the $W/T = 5.5$ plates.

Fig. 12—Casting soundness vs area of cells below Niyama criterion threshold value of $0.1 (K s)^{1/2}/mm$, for the $W/T = 10$ plates.

value is greater than 0.1 . Figures 10 through 12 show that, as the X-ray level of a plate increases, the area with Niyama values less than 0.1 tends to increase as well. The standard-deviation bars show that there is a large amount of scatter in these data, however. By considering Figures 10 through 12, it can be seen that the level 0 and 1 plates in Figure 9,

Fig. 13—Relationship between area of small Niyama values and feeding length-to-feeding distance ratio for simulations run with base casting conditions.

with $Ny_{min} < 0.1$, generally had very small areas with Niyama values less than 0.1. Thus, a small minimum Niyama value does not necessarily imply that the plate should have a high X-ray level; if the area with $Ny_{min} < 0.1$ is small, the plate may still be radiographically sound.

It is desirable to correlate the area with Niyama values less than the 0.1 threshold to the corresponding shrinkage X-ray level, but this is not a trivial process. Comparing Figures 10 through 12, it is evident that these areas depend on W/T . For example, the mean value for the level 4 plates in Figure 10 is 51.3 cm², while the corresponding mean values from Figures 11 and 12 are 16.5 and 78.8 cm², respectively. In an effort to remove this W/T dependence, simulations were run to try to correlate the area of Niyama values less than 0.1 from a given simulation to the geometry of the plate. The geometry was characterized by the coefficient $C_{soundness}$, which is the feeding length-to-thickness ratio (FL/T) for a plate with a given W/T value, divided by the feeding distance-to-thickness ratio (FD/T) for that value of W/T . Recall that the feeding distance is defined as the longest distance over which a riser can supply feed metal to produce a radiographically sound casting, whereas the feeding length is simply the distance between the riser and the furthest point in the casting fed by this riser, regardless of the soundness. Notice that, for a given plate, $C_{soundness}$ simplifies to FL/FD and, hence, is simply a length ratio indicating the extent to which the feeding length exceeds the feeding distance. The resulting correlations are shown in Figure 13. The hollow symbols indicate the simulation results, with circles, triangles, and diamonds representing the $W/T = 2$, 5.5, and 10 simulations, respectively. Note that all of these simulations were run for the same set of base casting conditions: AISI 1025 steel in a furan sand mold, 60 °C superheat, and $Ny_{min} = 0.1$ were used to determine the feeding distance. In other words, a series of plates were simulated in which the plate length was slowly increased for a given W/T value, and the feeding distance was defined as the feeding length when $Ny_{min} = 0.1$ was first reached. A value of $C_{soundness} = 1$ indicates that the feeding length is equal to the feeding distance. For each W/T value, the area of Niyama values less than 0.1 is zero for $C_{soundness} = 1$, because the $Ny_{min} = 0.1$ threshold was used to determine the feeding distance. Notice that there is a linear relationship between the results from all of the plate

Fig. 14—X-ray level vs soundness multiplier for the $W/T = 2$, 5.5, and 10 plates.

lengths simulated for a given W/T value, and that the slopes of the lines for the three different W/T values are different. The linear relationship for a given W/T value is not surprising; considering that, for the example Niyama plots shown in Figure 7, as the length of a simulated plate is increased, the region with $Ny < 0.1$ simply gets correspondingly longer (*i.e.*, it does not get thicker or wider). Although Figure 13 was produced by simulating everything at the base casting conditions listed previously, these results are valid for other casting conditions as well. As long as $C_{soundness}$ is calculated by evaluating both FD/T and FL/T for the *same* casting conditions, these linear relationships are still valid, because the deviation from the base casting conditions is the same in both the numerator and denominator. This was verified by running several simulations with casting conditions different from the base conditions, and the resulting values of $C_{soundness}$ were in agreement with the linear relationships shown in Figure 13.

Finally, the areas shown in Figures 10 through 12 were mapped onto Figure 13 to determine the corresponding value of $C_{soundness}$ for each plate. This coefficient was then plotted against the shrinkage X-ray level for that plate. The result is displayed in Figure 14. Notice that the W/T dependence has been removed, which is evident from the intermingling of the $W/T = 2$, 5.5, and 10 data. The mean values of $C_{soundness}$ are also included for X-ray levels 1 through 4, with bars indicating a standard deviation of 1 from the mean. Clearly, $C_{soundness}$ increases with shrinkage X-ray level. However, there is a large amount of scatter in $C_{soundness}$ for each X-ray level. This is due to the scatter in the experimental data that was not accounted for by the simulations (*i.e.*, the uncertainty inherent in assigning a shrinkage X-ray level to an X-ray and the presence of spherical gas porosity in some of the plates) and also to the differences between the recorded and actual casting conditions during the casting trials. An important point to notice in Figure 14 is that, as the X-ray level decreases toward level 0, the trend in mean X-ray level multipliers indicates a mean value of around 1.0 for level 0. Recall from Figure 13 that a multiplier of 1.0 corresponds to a zero area of Niyama values below the threshold value of 0.1. This indicates that, in the mean, radiographically sound plates have a minimum Niyama value greater than 0.1. On the other hand, the mean value of $C_{soundness}$ for level 1 is greater than 1.0. Thus, in the mean, level 1 plates have

a minimum Niyama value less than 0.1. This justifies the choice of $Ny_{\min} = 0.1$ as the threshold value for the transition between radiographically sound and unsound.

Statistically speaking, one can expect about two-thirds of the data in Figure 14 to fall within a standard deviation of 1 of the mean values. This information can be utilized to analyze the results of a simulation and to get an idea about what X-ray level is likely to result from producing the casting that was simulated, at the conditions used in the simulation. As a simple example, assume that an analysis was performed on the simulation results for some arbitrary plate. Assuming that the feeding distance is known (Part II of this article will provide equations and charts necessary to determine feeding distances), one could calculate $C_{\text{soundness}}$ simply by calculating the feeding length for the plate and dividing by the feeding distance. Suppose that a value of $C_{\text{soundness}} = 1.35$ was determined from this process. According to the data points shown in Figure 14, this could produce a plate with an X-ray rating anywhere between level 1 and 5. One could say, however, that there is a good chance (based on a standard deviation of 1) that the plate will be level 2, 3, or 4. And if multiple plates are produced under these conditions, the plates should, on average, be level 3 or better. Although this figure cannot exactly pinpoint the X-ray level based on simulation, it can give a range of likely X-ray levels, and this information can be used to determine if changes must be made to the casting design to produce an acceptable casting.

The relationships determined in Part I of this article between ASTM shrinkage X-ray level and both the minimum Niyama-criterion value and the area with $Ny < 0.1$ will be utilized in Part II to develop a new set of feeding-distance guidelines for low-alloy steel castings. It will be shown that these new guidelines are frequently less conservative than previously published rules, as well as being considerably more tailored to the casting conditions.

V. CONCLUSIONS

An extensive set of casting trials involving low-alloy steel plates was conducted in order to acquire a statistically meaningful set of experimental data relating the feeding lengths of cast steel sections to their corresponding shrinkage X-ray levels. These experimental data were then coupled with the results of corresponding numerical simulations in such a way that it was possible to develop a correlation between the Niyama criterion and ASTM shrinkage X-ray level. The results of this work indicate that, if the minimum Niyama value in a simulated cast steel section is greater than $0.1 K^{1/2} s^{1/2} \text{ mm}^{-1}$, the casting section should be radiographically sound. As the X-ray level increases, the minimum Niyama value tends to decrease toward an asymptotic limit of zero. A minimum Niyama value less than 0.1 does not necessarily indicate that the X-ray level will be greater than level 1, however. When the minimum value is below 0.1, one can look at the area in the cast section that has Niyama values less than 0.1. If this area is small (one or a few computational cells), the casting may still be level 1 or better. The area of $Ny < 0.1$ tends to increase as the X-ray level increases. This information was used to develop a soundness coefficient, $C_{\text{soundness}}$. This coefficient can be computed by knowing the geometry of the casting section of interest and the feeding distance for a casting section with the same W/T ratio. Once this coefficient is determined, it is possible

to get an idea of what the resulting X-ray level of that casting section will be. The uncertainty seen in the results presented here is thought to be due to three factors. In decreasing order of importance, they are (1) the uncertainty inherent in assigning a shrinkage X-ray level to a radiograph, (2) differences between recorded and actual casting conditions in the casting trials, and (3) differences in the amount of gas (as opposed to shrinkage) porosity in the casting-trial plates. The correlations between the Niyama criterion and ASTM shrinkage X-ray level developed in this article were used to develop a new set of guidelines for determining feeding distances for low-alloy steel castings. The development of these guidelines, as well as the guidelines themselves, are detailed in Part II of this article.

ACKNOWLEDGMENTS

This work was prepared with the support of the United States Department of Energy (DOE) Award No. DE-FC07-98ID13691. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors, and do not necessarily reflect the views of the DOE. We are indebted to Malcolm Blair and Raymond Monroe, SFSA, for their work in helping organize the trials and recruiting members to participate. Most importantly, we thank the participants in the plate casting trials for their substantial time and resource investment in all aspects of the Yield Improvement Program. This work could not have been accomplished without their shared efforts.

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