Prediction of burn-on and mould penetration in steel casting using simulation

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Burn-on and penetration defects in steel casting are principally caused by localised overheating of the sand mould or cores. Such overheating can cause liquid metal to compromise the mould surface and entrain onto the surface of the mould. A method has been developed to predict likely burn-on and penetration defect locations as part of a standard casting simulation. The method relies on determining, from simulation results, the locations where the mould is above a certain critical temperature. The critical temperature is generally above the temperature at which the steel is fully solidified. By measuring the time periods during which these locations in the mould are above the critical temperature, burn-on and penetration defects can be predicted. The method is validated through comparison with previous experimental data. Several parametric studies are conducted to investigate the sensitivity of the predictions to the choice of the critical temperature, the interfacial heat transfer coefficient between the steel and the mould, the pouring temperature, and the mould material. The results of one case study are presented where burn-on or penetration defects observed on a production steel casting are successfully predicted.

Keywords: Steel casting, Penetration, Burn-on, Simulation, Surface defects

Introduction

Burn-on (also known as burned-on sand or burnt-on sand) and metal penetration are common surface defects encountered in sand casting of steel. The glossary of foundry terms[1] defines burned-on sand as 'A misnomer usually indicating metal penetration into sand resulting in a mixture of sand and metal adhering to the surface of a casting. Sand adhering to the surface of the casting which (sic) is extremely difficult to remove. This condition may be due to soft moulds, poor sand compaction, insufficient mould coating paint, or high pouring temperature.' The repair or cleaning of burn-on and penetration defects after casting shakeout is not only costly, but can result in considerable delays in casting production. Although efforts have been made to understand the factors that lead to the formation of burn-on and penetration defects, there is currently no tool available to predict their occurrence in a reliable manner. With such a tool, the casting design cycle may be shortened and overall production efficiency may be increased.

Burn-on is a casting defect where liquid metal fills the voids in the sand mould or core without displacing the grains, causing sand, mould wash, or oxides to adhere to the casting surface. The adherents will only be defined as 'burn-on' if they are so strongly ingrained into the casting surface that the surface must be blasted or ground clean. The more massive penetration may be more easily removed by prying with a chipping hammer bit, depending upon the connectivity with the casting.

Burn-on is caused by liquid steel at the mould/metal interface penetrating shallowly into the mould. Typically, this occurs when the metal at the mould/metal interface stays hot enough for a sufficient amount of time to partially decompose the binder or the mould wash, while remaining partially liquid. Only then can the metal flow into the mold sand. The amount of time that is required for a burn-on defect to occur is unknown. However, the locations that have the greatest probability of experiencing burn-on are those where the metal beside the mould/metal interface remains partially liquid for the longest period of time. These locations, as a rule, tend to be in sharp corners, under risers, next to thick sections of castings, and on the surface of thin cores.[2] There, the mould tends to heat above the solidification temperature of the steel and remain at a high temperature for a relatively long period of time. Clearly, to understand burn-on defects, the interfacial region of the mould where the metal meets the sand must be analysed.

Penetration is quite similar to the burn-on defect, in that the presence of partially liquid metal at the mould/metal interface and local overheating of the mould are necessary conditions for the defect to occur. However, penetration is different from burn-on in that the metal penetrates deeper into the mould. The depth of the penetration defect is limited by the temperature of the mould away from the casting surface. Since the temperature of the mould usually decreases away from

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the mould/metal interface, the flowing metal will solidify, thereby stopping the penetration.[3] Therefore, the entire volume of the mould must be analysed to know not only where on the surface penetration is most likely to occur, but also to determine to what depth into the mould penetration is likely to reach.

Studies have been performed to understand both qualitatively and quantitatively the factors that cause burn-on and metal penetration.[2–10] Svoboda showed that burn-on and penetration are caused by a combination of three modes.[4] The first such mode is liquid state penetration of metal into the intergranular voids of the mould. Liquid state penetration is governed by capillary forces and head height pressure: when the head height pressure is greater than the surface tension resistive force, metal can penetrate into the mould. The second mode of penetration is vapour state penetration into the mould. The metallic vapour penetrates the mould and subsequently condenses into liquid and then solidifies. The solidified metal changes the surface tension properties, thereby aiding in further liquid state penetration described as the primary mode of penetration. The third mode found by Svoboda is chemical reaction penetration, where complex oxides are formed by the alloying elements, mould washes and sand. Svoboda suggested methods of reducing void sizes and changing chemistries of washes and sands to reduce the instances of penetration and burn-on defects.

Richards and Monroe showed that, in fact, the capillary pressure and head height do aggravate penetration instances.[3] They showed that penetration and burn-on are most likely to occur at the hottest locations on the casting surface, and that the depth of penetration is governed by the thermal profile found in cores and moulds. Richards and Monroe also showed that pouring temperature has little effect on instances of penetration, because the pouring superheat is only a small fraction of the absolute temperature. They found that proper coating, use of ventilation, and properly placed chromite and zircon sand can reduce penetration. Chromite and zircon sands are particularly beneficial in reducing penetration defects because of their relatively high thermal diffusivity, which tends to reduce local overheating. The partially solid metal was described as having an increased apparent viscosity. They suggest that 'dendritic lock-up,' at which the partially solid metal is no longer able to flow, occurs at a solid fraction of $\sim$60%.

Stefanescu and Giese, as well as Pattabhi *et al.*, devised a method of predicting penetration depth by considering mechanical penetration forces (both head height and capillary forces), dynamic penetration forces (pouring velocity), and the permeability of the sand.[5–7] Their predictive equation, which was implemented in an Excel Spreadsheet, was shown to accurately predict penetration depths at individually chosen locations. Richards *et al.* showed that the type of sand, and specifically the reclamation process used by the foundry, makes the largest difference in reducing instances of burn-on and penetration.[8] In summary, the previous research suggests a number of contributing factors that affect burn-on and penetration. Aside from the works performed by Stefanescu and Giese, and Pattabhi *et al.*, the studies offer mostly qualitative information regarding the effect of various casting variables and the likely locations for burn-on or penetration defects to occur.[5–7]

The present study shows how thermal analysis of the mould/metal interface and of the mould (including cores) can be used to accurately locate burn-on and penetration defects. The present method identifies the areas of localised overheating by performing a standard casting simulation and recording the times the predicted temperatures are above a certain critical temperature. These time duration results are then visualised on the surface of the casting or in the mould.

This paper is divided into five sections. The present simulation methodology is explained in the next section. A detailed comparison with experimental data from Richards *et al.* is presented in the third section.[8] In addition, parametric studies are performed to investigate the sensitivity of the results to the choice of the critical temperature, the interfacial heat transfer coefficient, the pouring temperature and the mould material thermal properties. The results of an industrial case study are shown in the fourth section. The final section summarises the conclusions from this study.

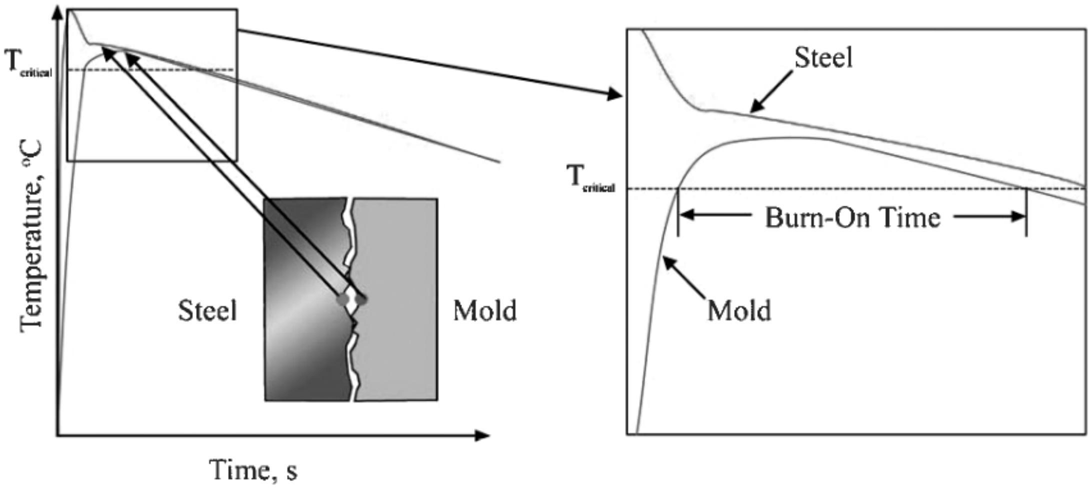
Method

There are numerous factors that contribute to burn-on and penetration defects, as mentioned in the Introduction. However, factors such as mould wash application and mould compaction cannot easily be accounted for in a quantitative manner. Therefore, it was decided to solely focus on the thermal effects. The principle interest of this study is to find the locations that have the highest probability of burn-on and penetration by calculating the times that the interface between the mould and the metal (for burn-on) and the mould (for penetration) stay above some, as of yet unknown, temperature. This temperature is referred to as the 'critical temperature' ($T_{critical}$ on figures) in this study and must be above the temperature at which the metal fully solidifies. Standard casting simulation is used to calculate the temperatures everywhere in the mould and metal and, then, to determine the times the temperatures are above the critical temperature.

Description of burn-on prediction

The prediction of burn-on is based on the time that both the temperature of the mould and the temperature of the metal at the interface between the two materials are above the critical temperature. The mould and the metal at the interface are generally at different temperatures because of the presence of a small air gap that forms during solidification of a casting. This is illustrated schematically in Fig. 1. The interfacial air gap acts as an insulator, keeping the steel hotter or the mould cooler. In a casting simulation, the effect of the air gap on the heat transfer is typically modelled by specifying an interfacial heat transfer coefficient. This heat transfer coefficient can be a constant or a temperature dependent function.

When obtaining the metal and mould interfacial temperatures from a casting simulation, care must be taken to interpolate the temperatures to the location of the interface, since they are often only predicted at discrete locations in the metal and the mould away from the air gap. As shown in Fig. 1, the time both interfacial temperatures are above the critical temperature is then measured. This time period is referred to as the 'burn-on time' in the present study. The burn-on times are



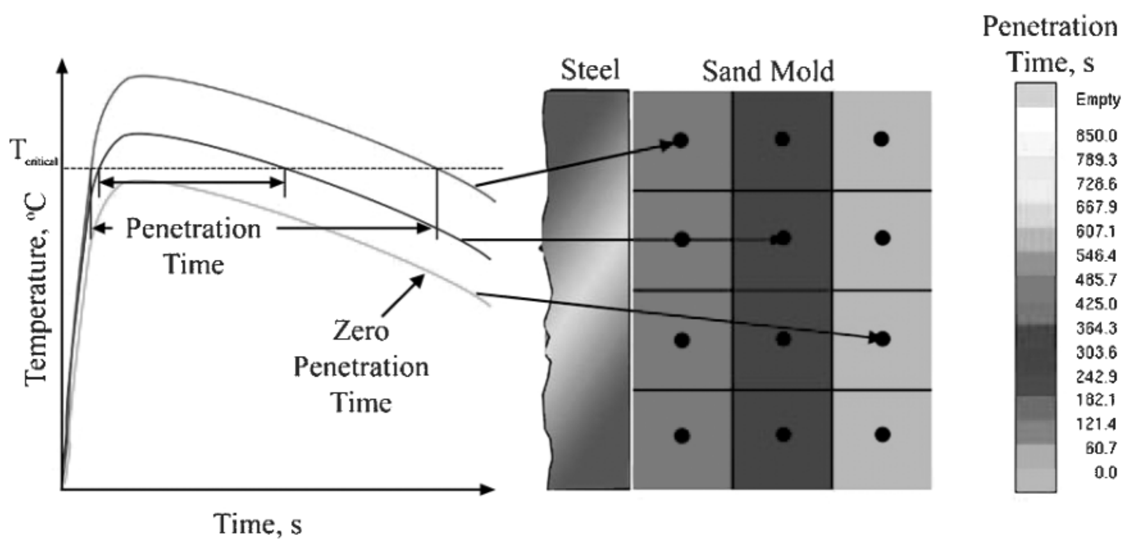
1 Schematic of method used to determine burn-on time from predicted temperature variations at mould/metal interface

obtained everywhere on the mould/metal interface and can be visualised as different colours on the surface of the casting using the post-processor of the casting simulation software. Since the metal at the interface is usually hotter than the mould, the mould surface temperature variation generally determines the burn-on time. Note that in many instances, the interfacial temperature of the mould will never be above the critical temperature; then, the burn-on time is simply assigned a value of zero. The regions on the mould/metal interface with the longest times above the critical temperature can be expected to most likely experience a burn-on defect. That being said, a large predicted burn-on time (relative to the casting solidification time) does not ensure that such a defect will indeed occur. The present method must be used in the context of the casting under consideration, and the role of the other factors mentioned in the Introduction (such as head height and mould wash) must not be forgotten.

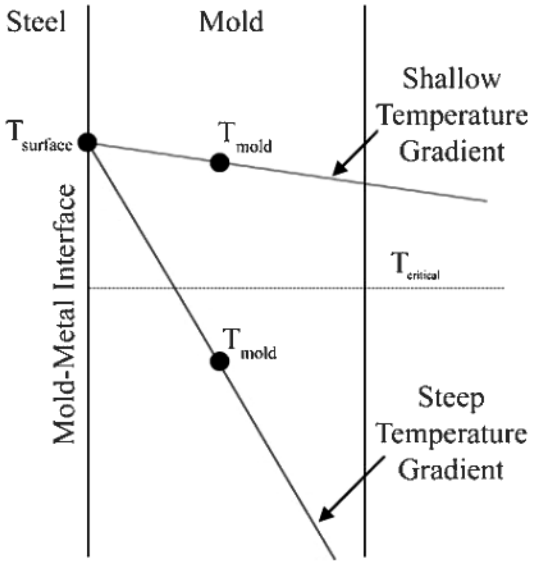
Description of penetration prediction

The prediction of penetration is similar to that for burn-on. However, the time above the critical temperature is determined everywhere in the mould (including the cores), rather than solely at the mould/metal interface. A schematic illustration of how the penetration times are measured from the predicted temperature variations in the mould is shown in Fig. 2. As in the burn-on prediction, locations in the mould that never reach the critical temperature are assigned a penetration time of zero. Finite penetration times are plotted as different colours inside the mould using the post-processor of the casting simulation software. They indicate likely regions for a penetration defect to occur. In particular, the likely depth of penetration, away from the casting surface into the mould, is visualised in this manner. Of course, sufficiently far away from the mould/metal interface the penetration times predicted in the mould are usually equal to zero.

Figure 3 illustrates the primary difference between the present burn-on and penetration predictions. If the temperature gradient in the mould near the mould/metal interface is very shallow, the predicted penetration times beside the interface will be similar in magnitude to the burn-on times. On the other hand, if the temperature gradient is steep, the two times will be quite different, and the penetration time near the mould/metal interface can be equal to zero even if the burn-on time is finite.



2 Schematic of method used to determine penetration time from predicted temperature variations in mould



3 Schematic of differences in burn-on and penetration predictions near casting surface that are caused by different temperature gradients in mould

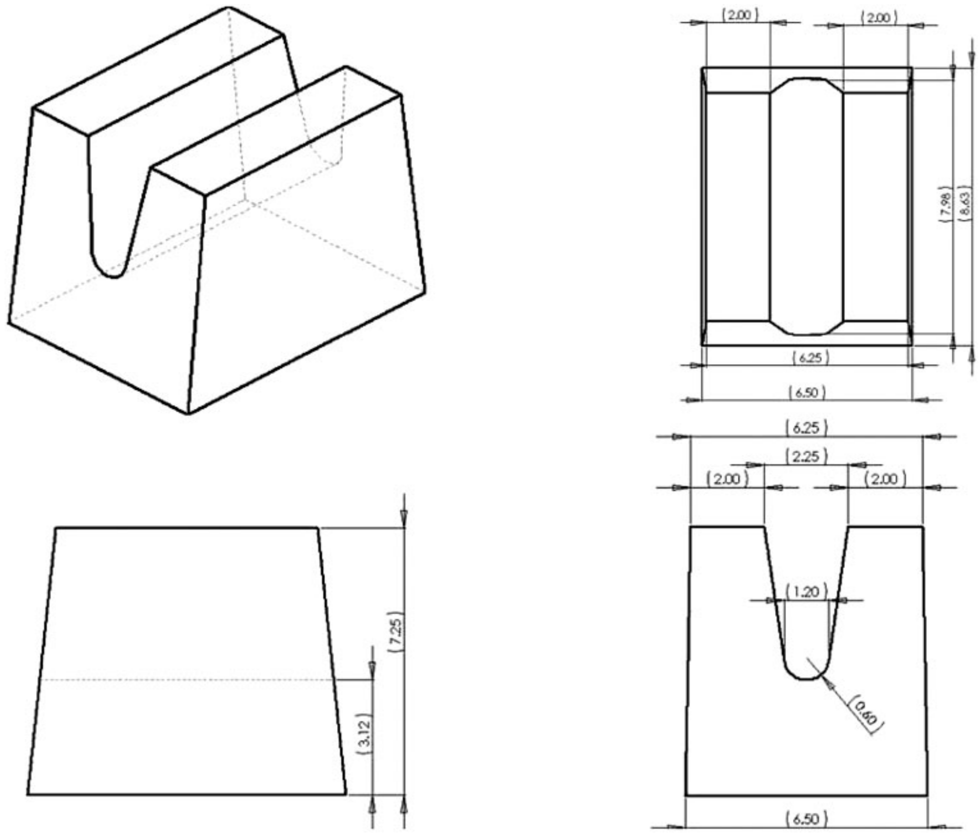
V-block: comparison with experiments and parametric studies

The present method for predicting burn-on and penetration defects is validated by comparison with experimental results obtained by Richards *et al.* for a casting referred to as the V-block.[8] Since an appropriate value for the critical temperature is not known currently, a parametric study is performed to investigate the sensitivity of the predictions to this temperature. A likely range for the critical temperature is identified. Since there is a relatively large uncertainty in the value of the interfacial heat transfer coefficient used in casting simulations, and the value of this coefficient can be expected to strongly affect the burn-on and penetration predictions, a second parametric study is presented to explore this effect. A third parametric study is conducted to explore the effect of the pouring temperature, since it has been reported to potentially affect the occurrence of burn-on and penetration defects and is often not known to great accuracy. Finally, a fourth parametric study investigates the effect of different mould material thermal properties on the burn-on and penetration predictions.

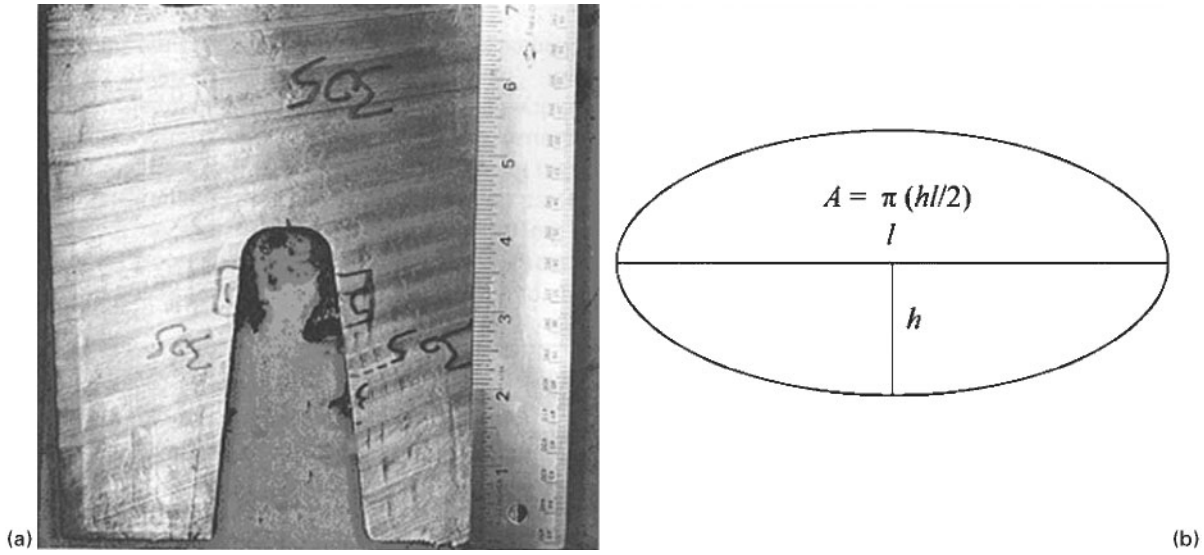
Review of V-block experiments[8]

The experimental casting used by Richards *et al.* was a V-block made of CF-8C stainless steel in a polyurethane no-bake (PUNB) sand mould (referred to as 'furan' in the present study).[8] The dimensions are provided in Fig. 4. The casting was 0·219075 m (8·625 in) long by 0·18415 m (7·25 in) high, with a gross pouring weight of ~69 kg (including the 0·1016 m (4 in) tall by 0·1524 m (6 in) diameter riser). The casting was designed to have a sharp internal corner, located under a large riser, surrounded by relatively thick sections. Thus, the burn-on or penetration defects always appeared in the 'notched' area under the riser (Fig. 5).

As shown in Table 1, the experiments were executed in a full factorial with four different parameters: sand (new or reclaimed), compaction (vibration or hand), work time/strip (immediate or delay), and coating (flow or brush). The extent of burn-on or penetration was quantified by measuring the area on the casting surface where the defects occurred. The defect area had approximately the shape of a folded ellipse (*see*



4 Dimensions of V-block (shown inverted – drag side up, without direct pour riser),[8] all dimensions shown in inches



5 *a* picture of slice of experimental V-block casting with burn-on or penetration defect area of 10 977 mm^2, ruler demarcations are inches[8] and *b* method for measuring elliptical defect area on casting surface

Table 1 Measured burn-on or penetration defect lengths, heights and areas for V-block from experiments of Richards *et al.*, for full factorial of four parameters[8]

Length, mm	Height, mm	Area, mm^2	Pour temp., °C	Pour time, s	Work time/strip	Compaction	Sand	Coating
36	38	2114	1603	9	Immediate	Vibration	New	Flow
76	82	9818	1599	9	Immediate	Vibration	New	Brush
47	27	1995	1588	10	Delay	Vibration	New	Flow
46	43	3117	1577	9	Delay	Vibration	New	Brush
127	50	9982	1575	8	Immediate	Hand	New	Flow
78	24	2944	1557	9	Immediate	Hand	New	Brush
71	51	5663	1546	9	Delay	Hand	New	Flow
77	26	3091	1539	11	Delay	Hand	New	Brush
125	51	10 072	1604	N/A	Immediate	Vibration	Reclaim	Flow
119	56	10 456	1577	~10	Immediate	Vibration	Reclaim	Brush
110	51	8796	1560	14	Delay	Vibration	Reclaim	Flow
118	59	10 980	1532	18	Delay	Vibration	Reclaim	Brush
108	74	12 461	1616	9	Immediate	Hand	Reclaim	Flow
83	38	4923	1611	~9	Immediate	Hand	Reclaim	Brush
83	34	4427	1608	9	Delay	Hand	Reclaim	Flow
110	54	9281	1599	N/A	Delay	Hand	Reclaim	Brush

Table 2 Averages of measured burn-on or penetration defect areas

	Area, mm^2	Standard deviation, mm^2
Thermally reclaimed ('new') sand	4665	2852
Mechanically reclaimed sand	8746	3316
Aggregate average	6568	3652

Fig. 5). No distinction was made between burn-on and penetration. The area was determined by measuring the total length l of the defect along the notch and its height h, from the centre of the notch to the lowest point along the side of the notch. Then, the defect area A is given by equation (1)

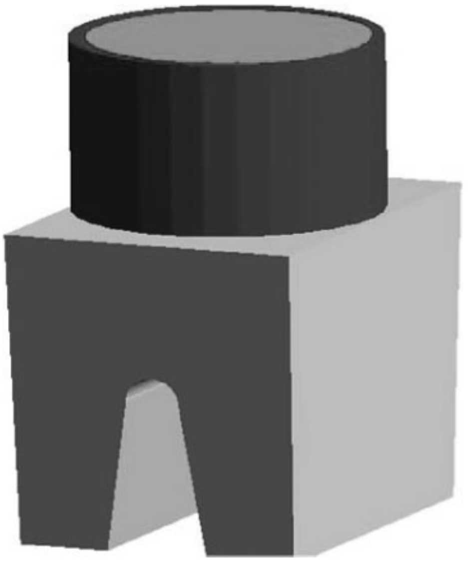
$$A = \pi\left(\frac{h \cdot l}{2}\right) \quad (1)$$

The measured length and height, and calculated area data is summarised in Table 1. A statistical analysis of the data revealed that, of all the test variables, only the type of sand ('new' or thermally reclaimed sand and mechanically reclaimed sand) had a significant effect on the measured burn-on or penetration areas in these experiments.[8] The averages of the measured defect areas for the two types of sand, as well as the average of all defect areas, together with the corresponding standard deviations, are provided in Table 2. It can be seen that the measured areas for thermally reclaimed ('new') sand are considerably below those for mechanically reclaimed sand.

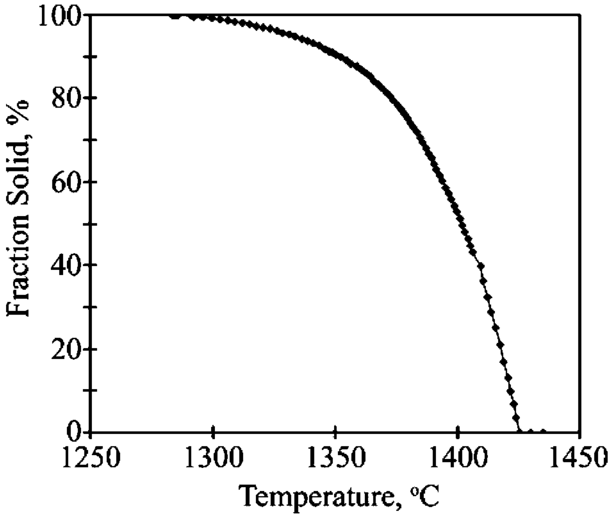
Simulation procedure

A solid model of the V-block casting was created and imported into the casting simulation software*. An image of the simulated casting is shown in Fig. 6, together with the riser and insulation. Not visible in

*MagmaSoft was used in the present study; however, the present method could be used with any casting simulation software.



6 V-block with riser and insulation



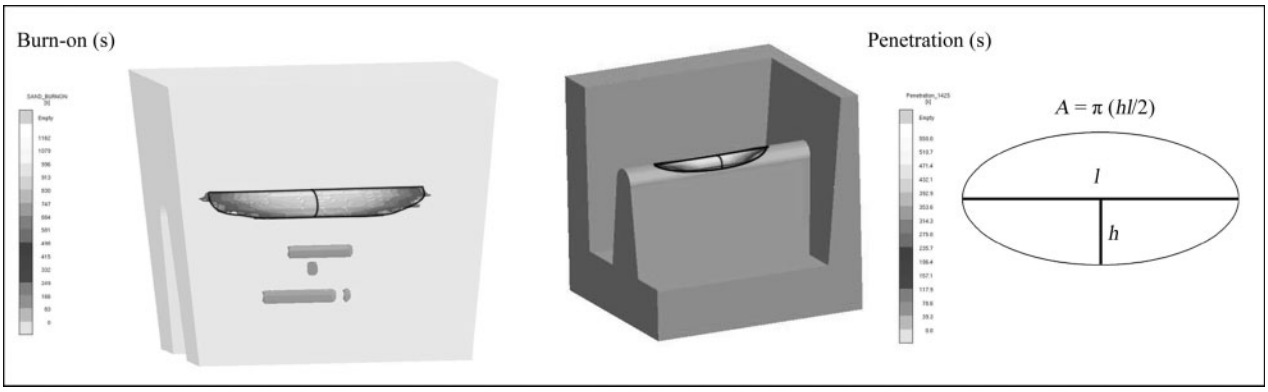
7 Fraction of solid curve for CF-8M stainless steel

Fig. 6 but nonetheless included in the simulation were a Foseco direct into mould pour system with the appropriately modelled filter. In the simulation, properties for CF-8M steel were used, because the properties for CF-8C steel were not available. Due to the similarity in the chemical composition of these alloys, small differences in the properties between these two alloys are not expected to significantly affect the burn-on and penetration predictions. For the baseline simulation case, a constant interfacial heat transfer coefficient of 1000 W m^{-2} K^{-1} was used. The mould filling process was simulated using a baseline simulation pour temperature (at the entrance to the mould) of 1556°C and a pour time of 10 s. This simulation pour temperature was obtained by taking the average of the pour temperatures listed in Table 1, which represent steel temperatures measured in the ladle immediately before pouring, and subtracting 25°C from the average measured ladle temperature to approximately account for the temperature drop of the steel from the ladle to the mould. Figure 7 shows the solid fraction versus temperature curve for CF-8M steel used in the V-block simulations. The temperature associated with 0% solid (1425°C) was used as the baseline critical temperature T_{critical}.

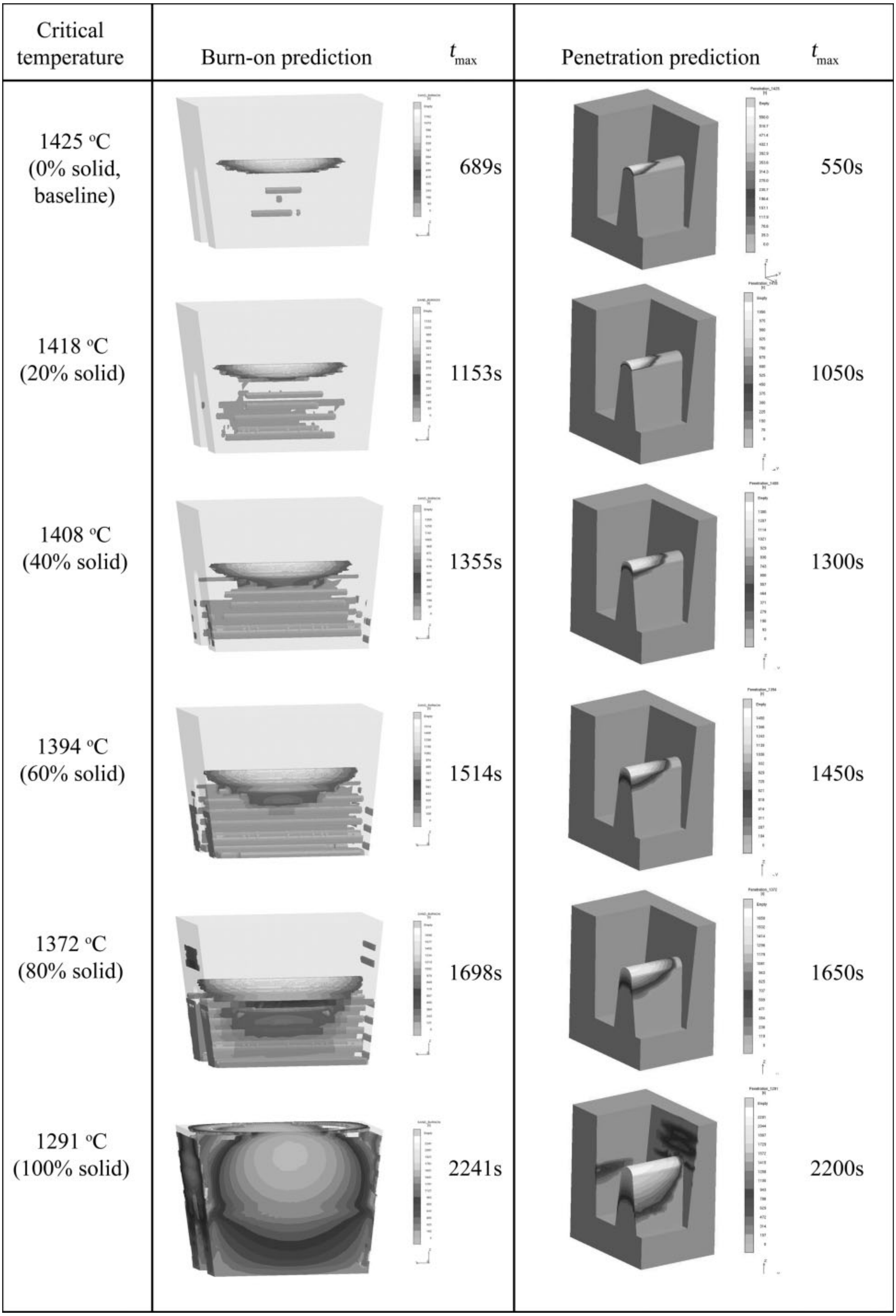
Baseline simulation results

Figure 8 shows the burn-on and penetration predictions for the V-block corresponding to the baseline parameter values provided above in the previous subsection. It can be seen that the predictions approximately coincide with the defect observed in the experiments (Fig. 5). All burn-on and penetration predictions are limited to the notch region. The predicted burn-on times on the casting surface increase toward the centre of the notch, with the maximum value equal to 689 s. As expected, the predicted penetration times inside the mould decrease with increasing distance from the mould/metal interface. The maximum penetration time predicted is equal to 550 s. The depth and volume of sand predicted to be penetrated appears to compare well to the amount of penetrated sand visible in the experimental V-block section shown in Fig. 5.

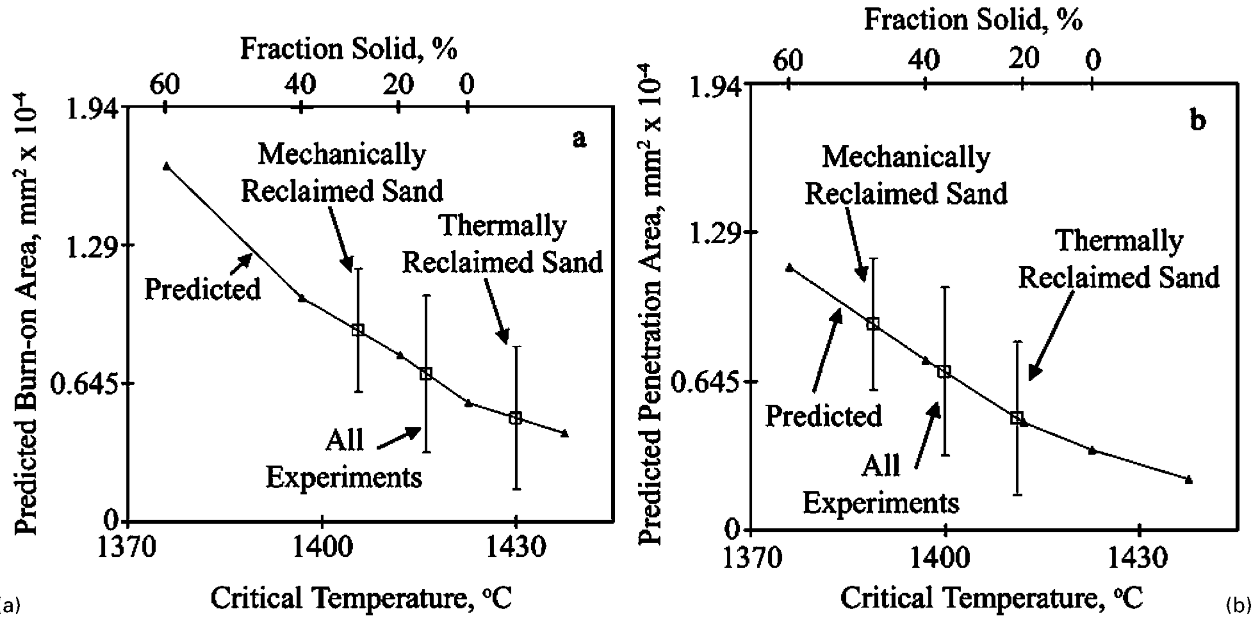
In order to allow for a more quantitative comparison between the predictions and the measurements of Richards *et al.*,[8] burn-on and penetration defect areas were determined from the simulation results in the following manner: the region on the casting surface where the burn-on time is predicted to be finite (i.e. above zero) represents the predicted burn-on area. As shown in Fig. 8, this area can be well approximated by a folded ellipse. The area of this ellipse was determined in the same manner as in the experiments of Richards *et al.* (*see* Review of Experiment section).[8] The area on the mould surface where penetration is predicted to take place (i.e. where the penetration time is finite) was calculated in the same fashion. Note from Fig. 8 that the penetration area is somewhat smaller than the burn-on



8 Predicted burn-on and penetration times for V-block baseline case



9 Parametric study no. 1: effect of critical temperature on burn-on and penetration predictions



10 ***a*** **variation of predicted burn-on area with critical temperature and comparison with experimentally measured areas; error bars are $\pm$1 one standard deviation;** ***b*** **variation of the predicted penetration area with critical temperature and comparison with experimentally measured areas; error bars are $\pm$1 one standard deviation**

area, indicating the presence of considerable temperature gradients in the mould near the mould/metal interface. Since the depth of penetration into the mould was not measured, no comparisons were made with those predictions.

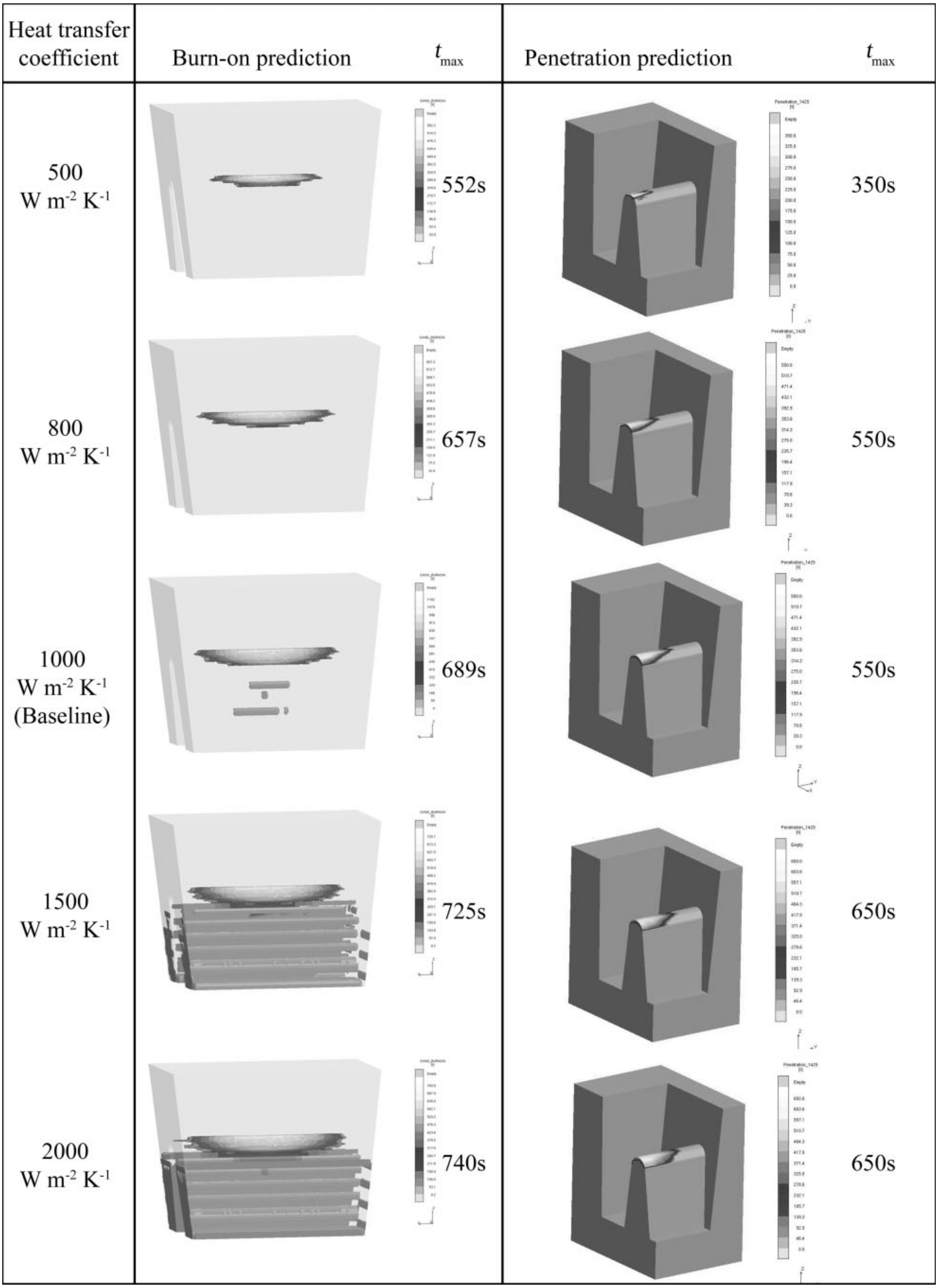
It should be mentioned that the present method of determining the burn-on and penetration areas for the V-block from the simulation results should be regarded as conservative. This is the case because all indications (within the region of interest) with finite burn-on or penetration times are included in the area calculations. The predicted areas would be somewhat smaller if, say, only the times above 100 s were included. Unfortunately, no information is available regarding the time necessary for burn-on or penetration to actually occur and a defect to form. In lieu of a more sophisticated model of the burn-on and penetration processes and considering the large scatter in the experimental data (*see* Tables 1 and 2), the present method of comparing the measured and predicted areas was deemed to be appropriate.

Parametric study no. 1: critical temperature

For burn-on or penetration to occur, the steel must be above the temperature at which it is fully solid. In fact, at a sufficiently large fraction of solid, the liquid metal will not be able to flow anymore, and metal penetration into the mould will cease. Any solid fraction can be directly associated with a temperature, according to the solid fraction versus temperature curve for the steel under consideration (*see* Fig. 7). The critical temperature used for the burn-on and penetration predictions should, thus, be viewed as the temperature at which the solid fraction is large enough to inhibit liquid metal flow.

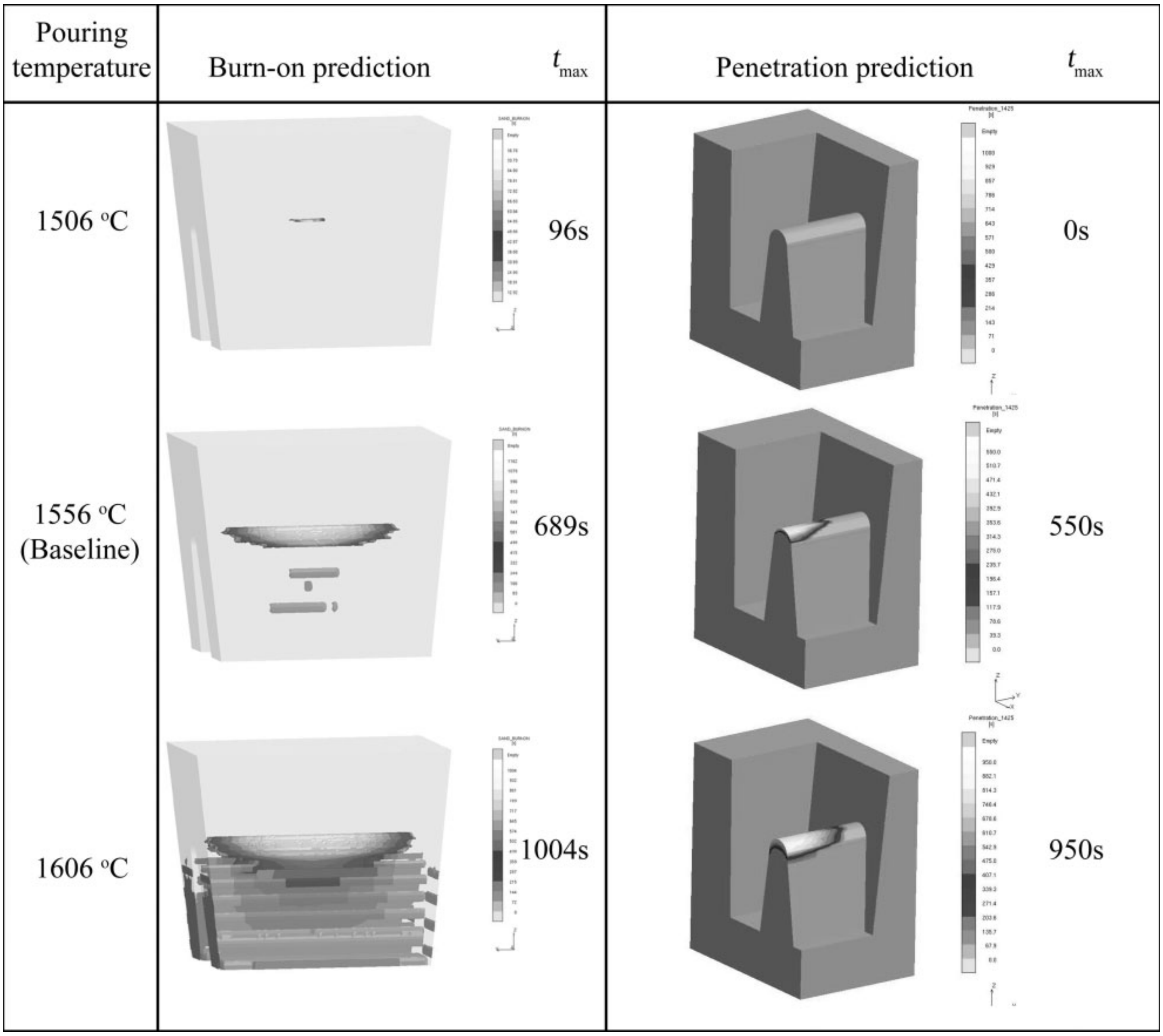
In order to illustrate the sensitivity of the burn-on and penetration predictions to the choice of the critical temperature, and to validate the present method, a parametric study was undertaken. Figure 9 shows the results of six simulations in which the critical temperature was varied from the 100% solid temperature to the liquidus temperature in steps corresponding to 20% increments in fraction solid. It can be seen that the predicted burn-on and penetration times and indications strongly increase with decreasing critical temperature. In fact, the predictions corresponding to critical solid fractions above about 80% can be considered unrealistic. For such high critical solid fractions (or low critical temperatures), large burn-on and penetration times are predicted even on the outer casting surfaces. For critical temperatures approaching the liquidus temperature, on the other hand, the predicted burn-on indications become reasonable. The burn-on and penetration predictions corresponding to critical solid fractions between 0% (baseline) and 60% appear to most closely correspond to the experimental results in Fig. 5.

A direct comparison between the measured and predicted burn-on and penetration areas is shown in Fig. 10*a* and *b* respectively. In these figures, the predicted burn-on and penetration areas are plotted against the critical temperature (and the corresponding solid fraction). The measured data corresponding to the averages listed in Table 2 are also included in the figures. They were shifted along the horizontal axis until the measured averages fell on the line corresponding to the predictions. This was done in an attempt to infer from the measured areas the correct critical temperature to use in the simulations. Since the measured areas vary considerably depending on the sand type and other experimental factors, only a range of critical temperatures can be identified that results in agreement between the measured and predicted burn-on and penetration areas. For the steel under consideration, this range can be seen to be between about 5°C above to 25°C below the liquidus temperature. That temperature range corresponds to critical solid fractions between about 0 and 30%. The aggregate mean of all measured areas is best predicted for a critical solid fraction of $\sim$15%, with the value being slightly lower in Fig. 10*a* (for burn-on) than in Fig. 10*b* (for penetration). For lower critical



11 Parametric study no. 2: effect of interfacial heat transfer coefficient on burn-on and penetration predictions

solid fractions (or higher critical temperatures), the predicted penetration areas would become too low, whereas the burn-on prediction would still be in agreement with experimental observations. For higher critical solid fractions (or lower critical temperatures), the predicted areas can become unrealistically large, as already noted in connection with Fig. 9. Considering the large variations in the measured areas and the



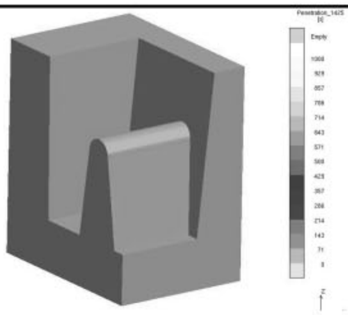
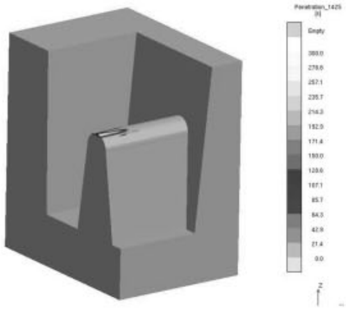
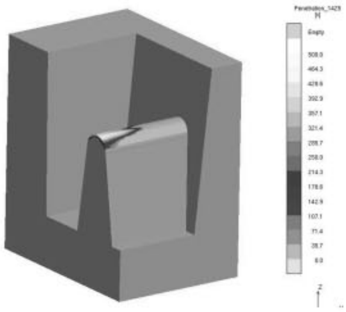
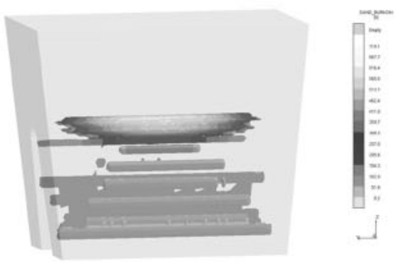
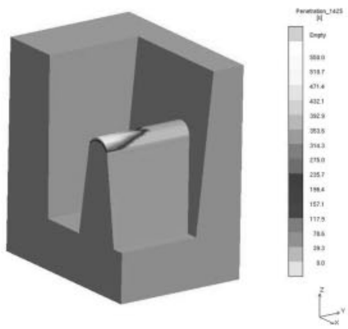
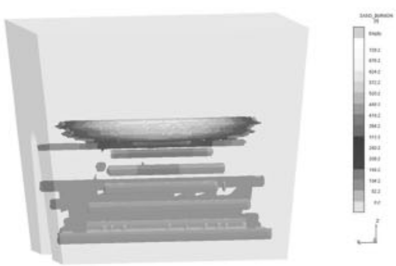
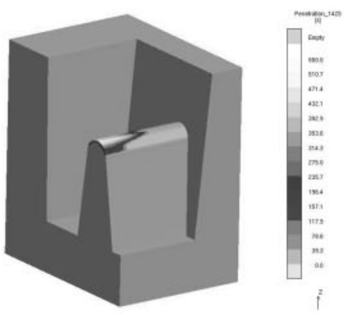
12 Parametric study no. 3: effect of simulation start temperature of steel on burn-on and penetration predictions

uncertainties in the simulation results, it seems most appropriate to conclude that any critical temperature corresponding to solid fractions between 0 and 50% provides reasonable burn-on and penetration predictions respectively. Note that the baseline case critical solid fraction of 0% falls at the lower end of this range. Also, it appears that there is a different appropriate critical temperature for the prediction of burn-on and penetration, such that penetration falls closer to the lower end of that temperature range (~40% solid) and burn-on tends towards the higher end (~10% solid).

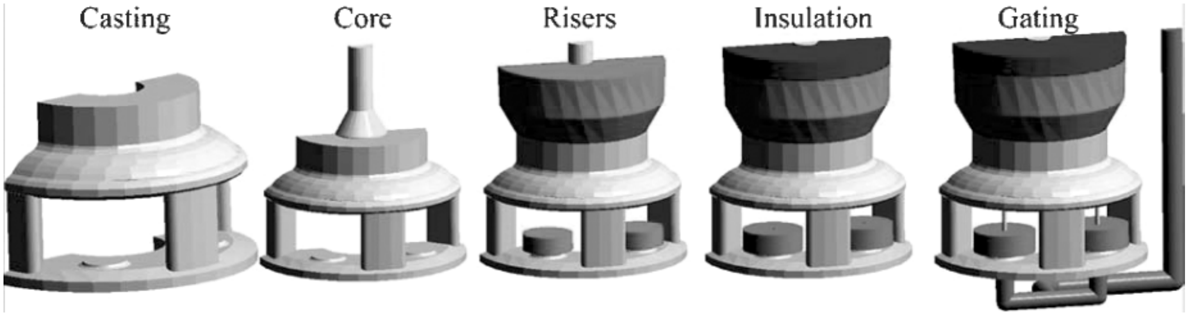
Figure 10 also indicates that the critical temperature is significantly different for mechanically and thermally reclaimed sand. Both burn-on and penetration occur at a lower critical temperature (higher critical solid fraction), by ~25°C on the average, for the mechanically reclaimed sand than for the thermally reclaimed sand. This observation is consistent with the physics implied in the post-mortem microstructure analysis conducted by Richards *et al.*[8] In the mechanically reclaimed sand, localised sintering of the sand and burn-out of residual binder char lead to a larger and broader pore size distribution in the sand as well as larger disruptions in the mould wash coating at the surface. This allows (colder) metal with a higher fraction of solid to permeate the mould surface and subsurface regions of the mechanically reclaimed sand.

Parametric study no. 2: interfacial heat transfer coefficient

In the second parametric study, the heat transfer coefficient at the mould/metal interface was varied. Five different simulations were performed with interfacial heat transfer coefficients of 500, 800, 1000, 1500 and 2000 W m^{-2} K^{-1}. The results are shown in Fig. 11. It can be seen that the predicted burn-on areas and times increase with increasing interfacial heat transfer coefficient. This can be explained by the mould surface reaching a higher temperature when the thermal resistance of the interfacial air gap is decreased. This increase in the burn-on and penetration areas and times is, however, relatively small. Therefore, within the range studied (500 to 2000 W m^{-2} K^{-1}), the predictions are relatively insensitive to the interfacial heat transfer coefficient. Interestingly, the maximum predicted penetration times for the five simulations change more than the maximum predicted burn-on times. This indicates that penetration is more sensitive to the thermal

Mold sand	Burn-on prediction	t_{max}	Penetration prediction	t_{max}
Chromite		410s		0s
Zircon		525s		300s
Green		719s		500s
Furan (Baseline)		689s		550s
Dry Silica		728s		550s

13 Parametric study no. 4: effect of mould material thermal properties on burn-on and penetration predictions



14 Five pictures of symmetric half of planetary gear casing for case study: each simulated element is identified above addition in picture

resistance of the interfacial air gap. It should be mentioned that the penetration times in Fig. 11 (as well as in Figs. 9, 12 and 13) were obtained with a relatively large integration time step of 50 s. Therefore, the predicted penetration times are only accurate to within 50 s, and can under predict times by up to 49 s.

Parametric study no. 3: simulation pouring temperature

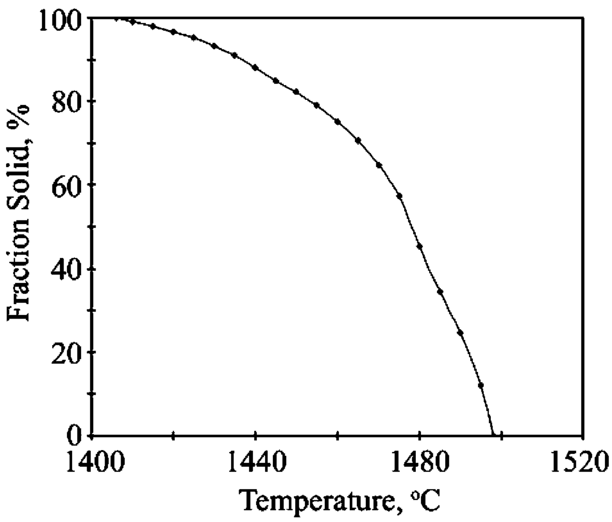
The pour temperature of the steel for the baseline case simulation (1556°C) represents only a rough estimate of the actual temperature of the steel as it enters the mould, as noted previously. Therefore, the effect of the simulation starting temperature on the burn-on and penetration predictions was investigated in a third parametric study. Simulations for three different starting temperatures were performed: 1506, 1556 (baseline) and 1606°C. The computed results are shown in Fig. 12. It can be seen that the simulation pouring temperature does indeed play a significant role in the prediction of burn-on and penetration. For an increase in the starting temperature of only 50°C, the predicted burn-on and penetration time nearly doubles. Furthermore, the predicted penetration volume increases by more than a factor of two. Whereas a decrease in pouring temperature of 50°C will reduce the prediction of burn-on and penetration to almost no indication. These changes in the defect area predictions are caused by the mould being heated to a higher (lower) temperature when the steel is initially at a higher (lower) temperature. A higher simulation pouring temperature obviously corresponds to a higher pour temperature in practice. Therefore, the present parametric study indicates that burn-on and penetration defects are sensitive to the pour temperature, despite the lack of statistically significant evidence in earlier work.[3]

Parametric study no. 4: mould material thermal properties

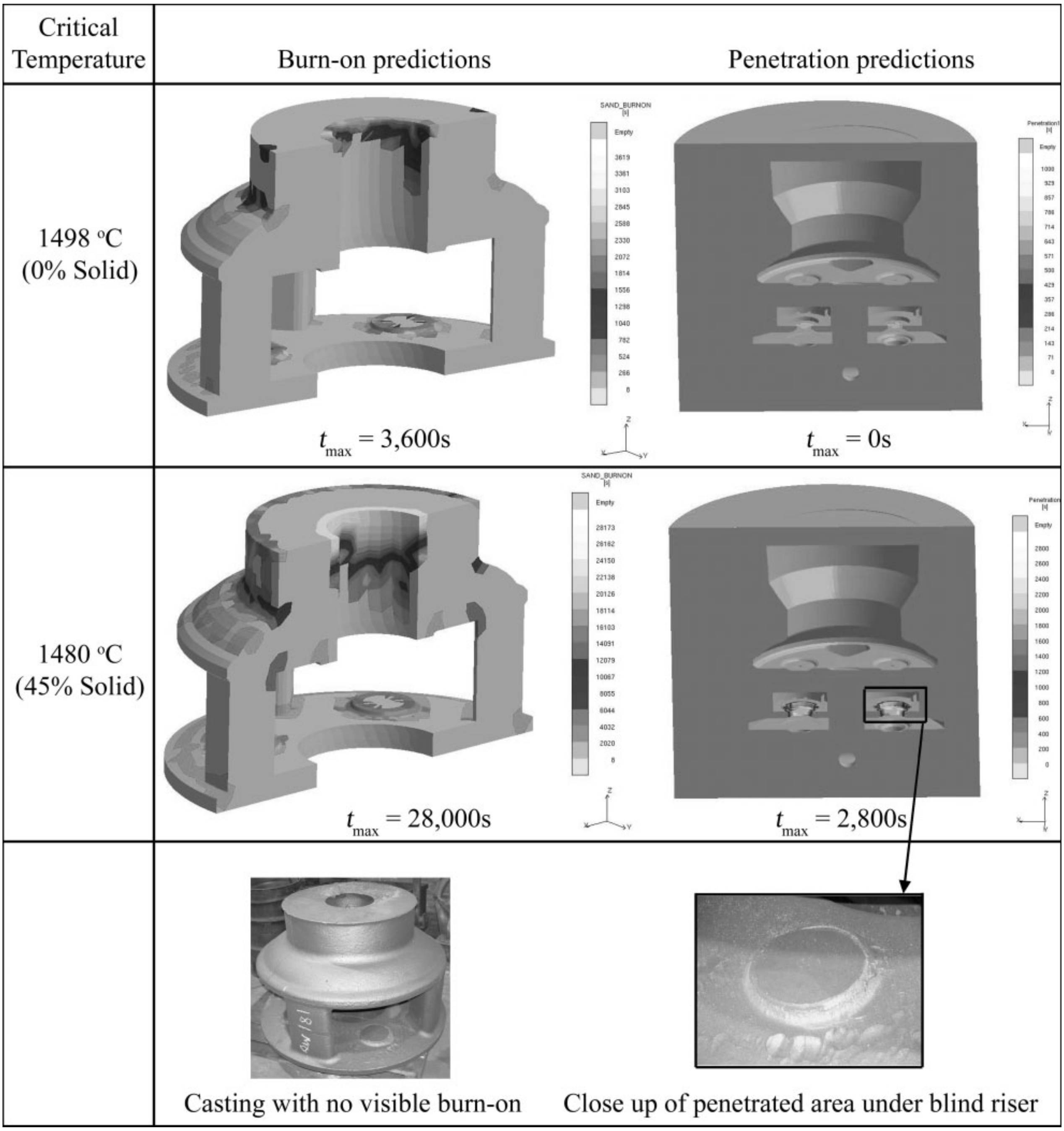
The sensitivity of the present burn-on and penetration predictions to the mould material thermal properties was investigated in a fourth parametric study. Five different sands were simulated: chromite, zircon, green, furan (PUNB, baseline) and dry silica. The thermal properties for these mould materials are available in the database of the casting simulation software used. The computed results are shown in Fig. 13. It can be seen that the type of mould material plays a significant role in the prediction of both burn-on and penetration. Using chromite sand and, to a lesser extent, zircon sand results in the least amount of burn-on and penetration being predicted. In fact, no penetration is predicted for chromite sand. This can be expected due to the relatively high thermal conductivity of those two sands, which tends to lower the temperature of the mould. Chromite is often used in foundries as a facing sand to reduce burn-on and penetration defects. By comparing the other three mould materials (green, furan and dry silica sand), Fig. 13 shows that furan has the smallest amount of burn-on time, but the largest penetration depth. For the dry silica sand mould, the most burn-on area and the longest penetration time are predicted. Overall, however, the differences in the burn-on and penetration predictions between these three mould materials are relatively minor.

Case study

A case study was performed where burn-on and penetration predictions were compared to observations on an actual production casting. The casting is a planetary gear casing, also known as a carrier gear, made of low alloy steel. The simulation setup for the case studies, including the values for all input parameters (pouring temperature, interfacial heat transfer coefficient, etc.) were provided directly by the foundry that produces this casting. No changes were made to the simulation setups. The case study performed was for the planetary gear casing shown in Fig. 14. The casting is modelled with GS30Mn5 steel (the solidification range is from 1406 to 1498°C), poured at 1600°C into a dry silica mould at 20°C. The interfacial heat transfer coefficient



15 Fraction of solid curve for GS30Mn5 steel



16 Comparison of predicted and observed burn-on and penetration defects for case study at two different critical temperatures, at 1498°C (0% solid) and 1498 °C (45% solid)

for this model was set to a constant 800 W m^{-2} K^{-1}. As shown in Fig. 14, the simulated symmetric half of this casting has a chromite core, a large riser at the top, and two small blind risers. The core is modelled with chromite sand. The gross pour weight of this casting is 5964 kg. The fraction of solid curve for the GS30Mn5 steel is shown in Fig. 15.

The case study was performed with two different critical temperatures. The first critical temperature was set equal to 1480°C, the temperature that corresponds to the feeding effectivity solid fraction used by the foundry, 45%; the second critical temperature was set equal to 1498°C, the liquidus temperature of the steel, 0% solid. In all cases, the mould filling process was simulated.

The results of the burn-on and penetration predictions for both critical temperature simulations are shown in Fig. 16, together with a picture of the actual casting. A maximum burn-on time of 28 000 s is predicted for the critical temperature associated with 45% solid, with numerous indications on both the inner and outer casting surfaces. With the critical temperature set to 0% solid, the maximum predicted time is greatly reduced to 3619 s, again with indications on the inner and outer surfaces. No burn-on defects were observed on the actual casting. This suggests that the upper limit of the critical temperature range is more representative of the actual observed burn-on on the test casting. In particular, the large burn-on times that are predicted on the upper part of the cylindrical inside surface, which never experiences burn-on or penetration, are in the location of the highly compacted chromite core beside this surface which prevents any burn-on defect from forming.

The penetration predictions are also shown in Fig. 16. Penetration is predicted to occur only underneath the bottom blind risers for the lower critical temperature simulation, and is not predicted using the higher critical temperature anywhere in the mould. The penetration prediction for the case study is in complete agreement with the observations made on the casting, as shown in Fig. 16. This again seems to confirm that the critical temperature for penetration tends to agree with the lower end of the predicted critical temperature range.

Conclusions

A method was developed to predict likely areas of both burn-on and metal penetration casting surface defects. The method relies on the temperature predictions from a standard casting simulation, and calculates the times the mould/metal interface (for burn-on) and the mould (for penetration) temperatures are above a certain critical temperature. The present model was validated through comparisons with previous casting experiments involving a V-block.[8] Good agreement was achieved between the measured and predicted burn-on and penetration defect locations. By matching the measured and predicted defect areas, the critical temperature was determined to correspond to the temperature within the solidification range of the steel under consideration where the (critical) solid fraction is $\sim$15%. However, realistic predictions were achieved for any critical solid fraction between 0 and 50%. It was also found that the critical temperature for mechanically reclaimed sand is significantly lower than for thermally reclaimed sand, which can be attributed to the larger pores in the mechanically reclaimed sand allowing metal permeation at a higher fraction of solid. Additional parametric studies were conducted to investigate the sensitivity of the predictions to the value of the interfacial heat transfer coefficient between the mould and the metal, the pouring temperature, and the mould material thermal properties. These parametric studies indicate that the casting parameters in a simulation must be chosen carefully in order to closely match the conditions for the actual casting. Otherwise, burn-on or penetration defects may be vastly over- or under-predicted. The present method was further tested by performing a case study involving an actual production steel casting that had burn-on and/or penetration defects. The case study seemed to confirm the observations of the parametric studies; specifically, that the penetration predictions were in complete agreement with the observations made in the foundry when the critical temperature was closer to the lower end of the determined temperature range. On the other hand, the burn-on predictions were sometimes overly conservative and showed areas on the casting surfaces that did not actually experience a burn-on defect. In particular, the predictions were extremely conservative when the critical temperature was placed at the lower end of the critical temperature range. When the critical temperature was closer to the higher end of the range, the predictions were in better agreement with observations. In applying the present method in foundry practice, it should be kept in mind that several of the factors that are known to affect burn-on and penetration defect formation are not taken into account. These factors include the metal head height, the type of sand reclamation, sand density, mould coating, and others. Nonetheless, the excellent accuracy of the penetration defect predictions should make the present method a valuable tool in the foundry industry.

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