



Sensitivity of a Multi-Physics DC Casting Model to Material Database Selection: Implications on Hot-Tearing and Cold-Cracking Prediction in an AA7050 Alloy

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Numerical process simulation is increasingly used to optimize direct-chill (DC) casting of aluminum alloys, yet crack-susceptibility predictions depend critically on the constitutive-property databases employed. This study presents a sensitivity analysis of the ALSIM DC casting model with respect to material database selection, using AA7050 billet (315 mm diameter) casting as a benchmark. Three casting scenarios—hot tearing (HT), cold cracking (CC), and healthy billets—were simulated using five databases spanning semi-solid and fully-solid regimes: Al-2 wt.% Cu, AA7050, and artificially strengthened AA7050XTR semi-solid databases, alongside AA1050 and AA7050 fully-solid (hardening) databases. The results show that the fully-solid database dominates the first principal-stress field, which governs the critical crack size (CCS) used as the CC susceptibility indicator, while the semi-solid database has limited effect on the integrated critical strain (ICS) used as the HT indicator. This insensitivity may arise because accumulated strain in DC casting is governed primarily by process conditions rather than material properties, revealing a fundamental limitation of strain-based HT criteria for alloy-to-alloy comparison. To address this limitation, an improved version of reserve strain value (RSV) concept is discussed as a complementary, material-sensitive HT indicator that may support future development of coupled HT-CC assessment methods. Practical recommendations for industrial database development are provided.

INTRODUCTION

The 7xxx series aluminum alloys are high-strength, heat-treatable alloys primarily developed for aerospace structural applications.^{1,2} In recent years, however, the automotive industry's drive toward lightweighting and improved crashworthiness has created growing demand for high-strength aluminum alloys for automotive applications.³ These components are produced through a variety

of downstream forming routes, including warm-forming and stamping of rolled sheets⁴ and extrusions for crash-absorption structures.⁵ In all cases, the feedstock is produced via the direct-chill (DC) casting process, making the quality and integrity of DC-cast billets and ingots a critical upstream requirement.⁶

DC casting is a semi-continuous production method for wrought aluminum alloys, invented in the 1930s and developed through the 1980s–2000s, valued for its robustness, relative simplicity, and well-controlled solidification conditions.^{2,7} Despite decades of industrial experience, cracking during or

after casting remains a persistent and costly challenge, particularly for high-strength 7xxx-series alloys. These alloys are widely used and are valued for their excellent strength-to-weight ratio and fracture toughness;^{1,8,9} however, they possess a wide solidification range (i.e., $\Delta T \approx 170^\circ\text{C}$ for AA7050) and high residual-stress levels that make them susceptible to both hot tearing (HT)¹⁰ and cold cracking (CC).^{11–13}

The challenges to minimize casting defects remain an active area of research. Recent comprehensive reviews confirm that mushy-zone characterization methods, HT criteria, and the associated simulation approaches for aluminum alloys are still evolving,^{6,14} while targeted experimental studies show that the HT tendency of AA7050 is sensitive to casting process variables, such as mold preheating temperature and casting geometry.¹⁰ This continued effort underlines that reliable, physics-based prediction of cracking during casting is not yet fully resolved, motivating the present work.

HT initiates in the semi-solid mushy zone during the final stage of solidification, when tensile thermal stresses develop and promote the opening of interdendritic cracks that cannot be filled due to the restricted feeding.^{2,7} A semi-solid alloy below the rigidity temperature has established a coherent solid network, but liquid films persist at grain boundaries, providing weak tearing resistance. If the tensile thermal stresses exceed the low semi-solid strength, or if the accumulated thermal strain exceeds the available semi-solid ductility while liquid feeding is insufficient, a volume deficit develops and HT may nucleate. Once formed, these cracks could propagate along interdendritic paths.^{7,15} HT susceptibility is strongly dependent on alloy composition, casting speed, cooling conditions, and grain structure; for example, no HT is observed in Al-4%Cu, which has a large eutectic fraction that ensures liquid feeding persists to low solid fractions, while Al-1%Cu with a narrower solidification range and minimal eutectic is strongly susceptible to HT due to poor liquid feeding at high solid fractions.¹⁶

CC occurs well below the solidus temperature when the as-cast metal is brittle (typically below 300°C for AA7050) and accumulated residual thermal stresses exceed the fracture toughness of the material in the presence of a sizable defect.^{11,12,17} CC often leads to catastrophic failure, rendering the ingot unusable and posing safety hazards to the casting personnel and equipment.¹⁸ This type of cracking is predominantly observed in high-strength 2xxx and 7xxx alloys as the main driving force is the residual stress field that builds up due to uneven cooling across the ingot cross-section during solidification and subsequent cooling.¹⁹

Although HT and CC are conventionally treated as independent problems, our previous work has suggested a possible connection: undeveloped micro-HT or other solidification defects (porosity,

inclusions) may serve as initiation sites for catastrophic CC.^{11,13} Lalpoor et al.¹¹ reported both interdendritic (HT-like) and transgranular features on AA7050 cold-crack fracture surfaces and found that inclusions exceeding a certain critical crack size at the billet center could trigger catastrophic failure.¹³ However, to date, no detailed mechanistic explanation or direct experimental proof of the connection between micro-HT and CC has been established, motivating the quest for unified predictive tools.

Multi-physics DC-casting process simulators such as well-established and tested ALSIM,^{20–22} couple thermal, fluid-flow, and mechanical modeling and include built-in crack-susceptibility indicators. To measure the HT susceptibility, integrated critical strain (ICS) is utilized, which quantifies the accumulated plastic strain in the mushy zone during the critical window of feeding difficulties up to the point of sufficient grain bridging, with higher values indicating greater susceptibility to HT.²² Meanwhile, to measure CC susceptibility, critical crack size (CCS) is used, which defines the critical defect size above which a pre-existing defect (e.g., micro-HT, porosity, inclusions^{13,17}) will propagate into a catastrophic CC in the brittle regime, with lower CCS values indicating higher susceptibility. Previous work demonstrated that ALSIM can qualitatively reproduce casting-trial outcomes when casting speed and melt-inlet geometry are varied.²³ However, each simulation requires an alloy-specific constitutive database spanning the liquid, semi-solid, sub-solidus, and hardening temperature regimes (some tens of degrees below solidus temperature where strain-hardening starts to become important). Obtaining such databases experimentally is costly and time-consuming, requiring specialized tensile-testing rigs capable of operating at temperatures from the mushy zone down to room temperature.^{24–26} For this reason, surrogate semi-solid databases, for instance, for an Al-2 wt.% Cu alloy,²⁷ are often used in place of alloy-specific semi-solid data, while a fully-solid database of the alloy of interest, for instance, AA7050 in Lalpoor et al.'s work,¹³ can be used to simulate DC casting, as a fully-solid database is more straightforward to obtain. However, the impact of this material database substitution on crack-prediction accuracy has, until now, not been systematically quantified.

This paper substantially extends the preliminary study by Subroto et al.,²³ which established the modeling framework and provided qualitative trial benchmarking along with experimental observation of the failed billets, by presenting a systematic sensitivity analysis of the ALSIM model's response to material database selection in different temperature regimes. In this study, semi-solid databases (Al-2 wt.% Cu, AA7050, AA7050XTR) and fully-solid databases (AA7050, AA1050) across three industrially relevant casting scenarios (HT, CC, and healthy) will be compared, with two objectives: (1)

to quantify which part of the constitutive database is most critical for crack-susceptibility predictions, and (2) to provide practical guidance for industrial database development that balances accuracy against characterization cost. An additional aim of this work is to demonstrate, for the first time, a potential route by which HT formation can be quantified at the macroscopic scale and, through that quantification, linked to CC within a bulk-level finite-element model. The intent is not to deliver a fully validated industrial prediction tool, which is not yet possible at the current state of the art. To the best of the authors' knowledge, this HT $\rightarrow$ CC link has been suggested in our previous works,^{12,23} and to date been discussed only in qualitative or semi-quantitative terms; establishing a workable route to quantify it is, therefore, a principal contribution of this work. Full statistical and industrial-scale validation lies outside the scope of the present paper and is identified as future work. To quantify HT occurrence, an improved version of reserve strain value (RSV) concept is proposed as a complementary, alloy-specific HT indicator for further development toward quantitative HT prediction. The original RSV concept is inspired by the work of Novikov,⁷ who in the 1960s introduced the notion of a "reserve of plasticity", defined as the difference between the strain to failure of a semi-solid material and the thermal contraction accumulated during solidification. In the present work, this idea is further developed, anchored by results from experimental work, and implemented within the ALSIM finite-element framework to enable location-specific evaluation of HT susceptibility and its potential connection to CC.

METHODOLOGY

Benchmarking Context: AA7050 DC Casting Trials

Three cylindrical AA7050 billets (diameter 315 mm) with chemical composition specified in previous work²⁸ were DC-cast at Tata Steel Research & Development (IJmuiden, The Netherlands) under controlled conditions designed to produce distinct cracking outcomes. All billets were grain-refined with Al5Ti1B (2.5 kg/t), degassed in the furnace at 730°C, and cast at a melt temperature of approximately 680°C. The casting parameters, summarized in Table I, were selected based on

extensive casting-practice experience to reproducibly achieve the desired cracking states.

Billet 1 produced a classical centerline HT, Billet 2 produced CC propagating throughout the billet, while Billet 3 remained healthy with no visible fracture. These trials were reported previously²³ and serve as the references for the sensitivity study.

ALSIM Numerical Model

ALSIM is a finite-element process simulator developed by the Institute for Energy Technology (IFE, Norway) in collaboration with industrial and academic partners.^{20–22} It couples thermal, fluid-flow, and mechanical calculations in a framework specifically designed for aluminum casting processes. To optimize the simulation time, two-dimensional simulations were carried out including the melt distributor, mold, water-jet impingement zone, bottom block, and cast domains. Owing to the axial symmetry of round billet casting, all simulations were performed on a half-geometry to further decrease the simulation time. The solidification path of an AA7050 alloy was computed using JMatPro software²⁹ with the Scheil approximation. Other key casting simulation parameters such as heat-transfer coefficients can be found in the previous work.²³

The characteristic element size in the general casting region was approximately 2.5×2.5 mm, with adaptive mesh refinement applied in the mushy zone near the coherency isotherm, where the steepest temperature and solid-fraction gradients occurred, reducing the local element size to approximately 1.25×1.25 mm. Billet growth was represented using ALSIM's expanding-geometry formulation, in which new rows of elements were incrementally added to the Lagrangian domain as casting proceeded. Thermal time steps were controlled by a maximum allowable temperature change of 5°C per step, with bounds of 0.001–0.02 s, while the mechanical time step was fixed at 0.2 s throughout the simulation. The mechanical and pressure problems were solved using a direct sparse solver (PARDISO), whereas the thermal problem employed a conjugate-gradient iterative solver. Plastic strain iterations were converged to a global criterion of 1×10^{-8} , with a maximum of 40 iterations per time step. It should be noted that the numerical settings adopted here reflected values accumulated through the iterative development and

Table I. DC-casting trial parameters and outcomes

Parameter	Billet 1 (HT-condition)	Billet 2 (CC-condition)	Billet 3 (healthy)
Inlet geometry	Vertical (spout)	Semi-horizontal (40°)	Semi-horizontal (40°)
Nominal casting speed (mm/min)	50	90	50
Water flow rate (l/min)	40	110	40
Cracking outcome	Centerline HT	CC throughout billet	No visible cracks

Table II. Material databases used in this study

Database	Temperature regime	Origin / key characteristic
Al-2 wt.% Cu	Semi-solid + creep	Ludwig et al.; ²⁷ grain-refined binary alloy; standard ALSIM surrogate.
AA7050	Semi-solid + creep + hardening	Subroto et al.; ^{24,26} and Lalpoor et al.; ¹² alloy-specific, high-strength
AA7050XTR	Semi-solid only	Artificial: based on AA7050 with p , α_0 , α_1 multiplied by 10; extreme cohesion for sensitivity test
AA1050	Fully-solid hardening only	Van Haaften et al.; ³¹ soft, ductile, commercially pure Al

validation of the ALSIM modeling framework across multiple published DC-casting studies.^{17,20,22,30}

Constitutive Modeling Across Temperature Regimes

The mechanical behavior of aluminum alloys changes dramatically across the solidification range due to the evolving morphology, strength, and ductility of the solid-liquid mixture.^{7,25,28} ALSIM considers these different phenomena by employing three distinct constitutive models for different temperature regimes, as explained in the following paragraph.

As the billet solidifies and cools from the liquidus to room temperature, distinctly different deformation mechanisms become active, each described by a dedicated constitutive model within a unified framework. Above the coherency temperature ($T_{\text{coherency}} < T < T_{\text{liquidus}}$), no solid skeleton exists as grains (dendrites) are surrounded by continuous liquid volume; no mechanical model is applied in this non-coherent slurry zone and only the liquid pressure and mass conservation equations are solved. Between the solidus and coherency temperatures ($T_{\text{solidus}} < T < T_{\text{coherency}}$), the coherent mushy zone is treated as a two-phase viscoplastic porous medium, where both deviatoric and volumetric viscoplastic deformations are active alongside elastic strains, and the ICS HT indicator is used within this regime of semi-solid material. When the alloy is fully solidified, deformation is governed by two sub-models separated by a transition temperature, T_0 ; where, at temperatures below T_0 , strain hardening becomes significant. Above T_0 ($T_0 < T < T_{\text{solidus}}$), a power-law creep relationship governs deformation where strain hardening is negligible. Below T_0 , down to room temperature, an extended viscoplastic formulation incorporates temperature-dependent parameters capturing both strain-rate sensitivity and strain-hardening behavior of the alloy during deformation in this temperature regime (henceforth, called the “hardening” model); the CCS indicator is used in this low-temperature regime. Across all regimes, the governing equations are solved within a single finite-element framework, with the mushy zone formulation naturally

reducing to the fully solid when the solid fraction reaches 1. The details of each model have been described in previous studies and can be found elsewhere.^{12,20,22,27}

Material Databases and Simulation Matrix

Four distinct databases were utilized in this work as summarized in Table II.

The Al2 wt.% Cu alloy has been the incumbent database used in ALSIM for the semi-solid and creep regimes when the alloy-specific data is not available. Developed from extensive rheological experiments on grain-refined Al-Cu alloys and widely used in previous ALSIM studies.²⁷

AA7050 is a dedicated database obtained from tensile testing of as-cast AA7050 in the sub-solidus regime and super-solidus/semi-solid regime.^{24,26} For the hardening regime, data from Lalpoor et al.¹² were used.

AA7050XTR is an artificial semi-solid database created by multiplying key rheological parameters (p , α_0 , α_1) of the AA7050 database by a factor of 10, designed to test the model’s response to extreme semi-solid property variations, where α_0 governed the initial rate of force increase at small displacements, independent of solid fraction, and α_1 controlled the amplification of this rate with increasing solid fraction, explaining the progressively steeper initial slopes observed at higher solid fraction (f_s) values; meanwhile, the parameter, p , defined the saturation force level at large displacements. AA7050XTR should not be interpreted as a physically realistic AA7050 database, but rather as an artificial upper-bound sensitivity case. Such exaggerated values were used to evaluate whether the ICS indicator responded strongly to large changes in semi-solid constitutive properties. Therefore, AA7050XTR was used here as a numerical sensitivity probe rather than as a realistic material state. To appreciate the difference of semi-solid tensile strength between AA7050 and AA7050XTR, simulated tensile test using rheological parameters for corresponding alloys, tested at different temperature/solid fractions is shown in Fig. 1.

AA1050 is a database for the fully-solid hardening regime of commercially pure aluminum alloy.

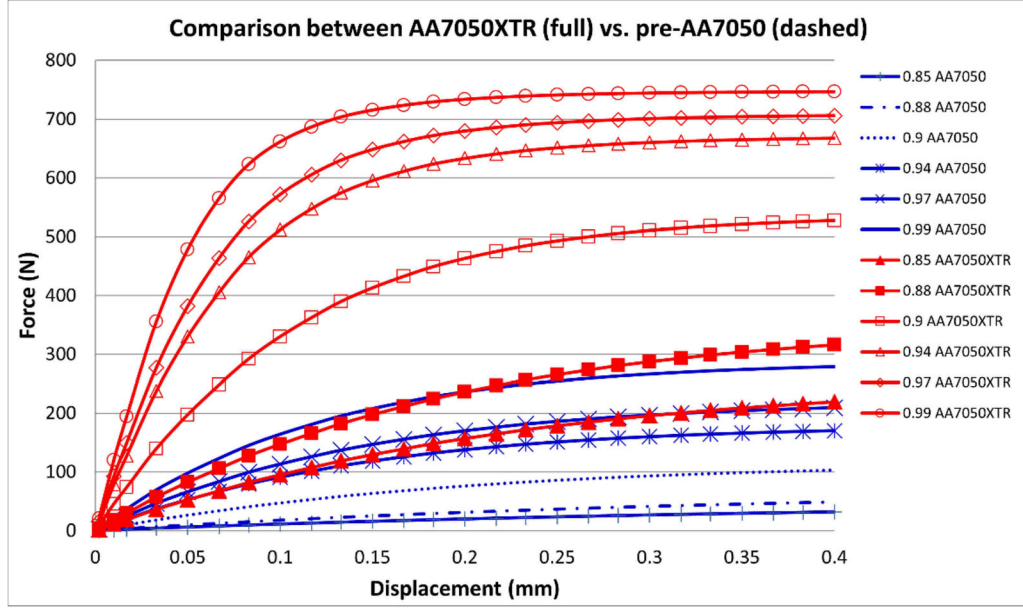


Fig. 1. Comparison of tensile force–displacement curves from the semi-solid constitutive model for AA7050 and AA7050XTR at different solid fractions ($f_s = 0.85–0.99$), illustrating the extreme strengthening in AA7050XTR due to the $\times 10$ amplification of cohesion parameters, ρ , α_0 , α_1 . The simulated AA7050 tensile-test data follow the methodology of Subroto et al.²⁶ The data shown are original to this study.

Table III. Simulation matrix–database combinations across different casting scenarios

Trial no.	Scenario	Semi-solid database	Fully-solid (hardening) database
1	Healthy	AA7050	AA7050
2	CC	AA7050	AA7050
3	HT	AA7050	AA7050
4	HT	AA7050XTR	AA7050
5	CC	AA7050	AA1050
6	HT	Al-2 wt.% Cu	AA7050

AA1050 is significantly softer and more ductile than AA7050,^{31,32} providing a stark contrast that tests the model’s sensitivity to fully-solid properties and CCS calculation.

To assess the sensitivity of the ALSIM model with respect to different materials databases in different temperature regimes, several simulation cases were carried out, and the scenarios are shown in Table III. The trial cases employed different casting process parameters using the incumbent Al-2 wt.% Cu database in the semi-solid regime and AA7050 in the fully-solid hardening temperature regime as has been carried out in previous work.²¹ The focus in this work was on using a complete AA7050 database on both the semi-solid and fully-solid temperature regimes as the baseline (Trials 1–3) following the process conditions in the previous work as shown in Table I. The sensitivity of HT susceptibility through ICS was assessed by employing different versions of AA7050 semi-solid database under identical HT casting conditions (Trial 3 versus Trial 4). To assess the sensitivity of the fully-solid hardening database and CCS calculation, the CC case simulation was

run comparing AA1050 and AA7050 in the fully-solid hardening temperature regime under identical CC casting conditions (Trial 2 versus Trial 5), while Trial 2 versus Trial 6 compares the effect of different semi-solid database, i.e., Al-2 wt.% Cu, that was used in the previous study.²³

Crack-Susceptibility Indicators

To calculate the HT susceptibility, ICS is used. The ICS criterion accumulates the viscoplastic strain experienced by the mush during the feeding-difficulty window, integrating the plastic strain rate when the liquid pressure falls below a critical value ($p_c = -7000$ Pa) and the solid fraction is below the no-feeding solid fraction ($f_s = 0.99$).²² Higher ICS values indicate higher HT susceptibility. Critically, the ICS formulation is strain-based and does not directly incorporate stress magnitude or material strength.

Meanwhile, to calculate CC susceptibility, CCS is employed. This criterion is derived from linear-elastic fracture mechanics, where a_c (half of CCS),

depends on the crack initiator shape as shown in Table IV, where K_{Ic} is the plane-strain fracture toughness (temperature-dependent, experimentally measured for AA7050 by Lalpoor et al.¹²) and σ_{11} is the first principal stress from the ALSIM mechanical calculation. Lower CCS values indicate higher CC susceptibility.

SIMULATION RESULTS

Mechanical Calculation

The comparison of the first principal stresses for the simulation cases that use the complete AA7050 materials database, i.e., AA7050 materials databases in both semi-solid and fully-solid (hardening) temperature ranges, is shown in Fig. 2a–c (or Trials 1–3, respectively). The comparison with simulations using the semi-solid Al-2 wt.% Cu material database²³ showed that the first principal stress distributions in each corresponding casting scenario, for example, between the HT case in Subroto et al.²³ and the HT case with the complete AA7050 database (Trial 3; Fig. 2c), were similar. Moreover, there was only a small difference in terms of maximum and minimum first principal stress between the cases with semi-solid Al-2 wt.% Cu material database²³ (an example from one of those cases, i.e., HT-case in Trial 6 in Fig. 2f) and semi-solid AA7050 material database (Trials 1–3 in Fig. 2). In all cases, the maximum and minimum value difference between the corresponding casting scenarios was within approximately 5 MPa.

To observe the sensitivity of different semi-solid materials database, Trial 3 (AA7050; Fig. 2c), Trial 4 (AA7050XTR; Fig. 2d), and Trial 6 (Al-2 wt.% Cu) were compared. All trials utilized the HT casting scenario. From this comparison, a marginal difference in terms of the first principal stress result was observed. Both the stress distribution and the minimum stress values were similar; additionally, the difference between the maximum stress values was relatively low (within 3 MPa).

The most significant difference in terms of the first principal stress calculation occurred when the fully-solid (hardening) materials database was varied. For this analysis, the CC scenario was employed as the benchmarking case. Based on Subroto

et al.,²³ the CC case produced the highest first principal stress among other casting scenarios. This selection was therefore considered optimal for isolating the effect of different fully-solid (hardening) material databases on CCS predictions. To observe this effect, Trial 2 (AA7050; Fig. 2b) and Trial 5 (AA1050; Fig. 2e) were compared. The comparison revealed a significant difference in the resulting first principal stress. Although the stress distributions were qualitatively similar, Trial 5 yielded a significantly lower first principal stress, ranging from -1.5 MPa to 47 MPa, compared to Trial 2.

Influence of Materials-Database Selection on Crack-Susceptibility Indicators (ICS and CCS)

Figure 3 shows the comparison of ICS values across the different simulation cases. Compared with the previous work,²³ the corresponding casting scenarios showed no significant difference in ICS values or spatial distribution. For the HT scenario specifically, ICS results were also largely insensitive to the choice of semi-solid database: the full AA7050 (Trial 3; Fig. 3c), AA7050XTR (Trial 4; Fig. 3d), and Al-2 wt.% Cu²³ (Trial 6; Fig. 3e) databases all produced similar ICS trends (Fig. 3c–e). Comparing maximum ICS values across cases using the full AA7050 mechanical database (semi-solid and fully solid), the healthy case (Trial 1; Fig. 3a) gave the lowest ICS, followed by the CC case (Trial 2; Fig. 3b), with the HT case (Trial 3; Fig. 3c) giving the highest. This ordering, healthy < CC < HT, matches the trend in our previous work using the Al-2 wt.% Cu semi-solid database.²³

Figure 4 shows the ICS value comparison of simulation cases with different semi-solid databases (AA7050, AA7050XTR, and Al-2 wt.% Cu).²³ This plot was taken at the centerline of the billet starting from just above the bottom block up to a billet length of 500 mm, and shows that the ICS value had a similar trend for all semi-solid databases; there was a peak value in the start-up phase and subsequently the value decreased, becoming stable at a value around 0.00025. This figure also shows comparable ICS values between simulations with the semi-solid Al-2 wt.% Cu database and the AA7050 database. AA7050XTR produced a marginally lower overall ICS, but the difference was small relative to the $\times 10$ change in constitutive parameters, demonstrating that the ICS criterion is weakly sensitive to semi-solid material property variations.

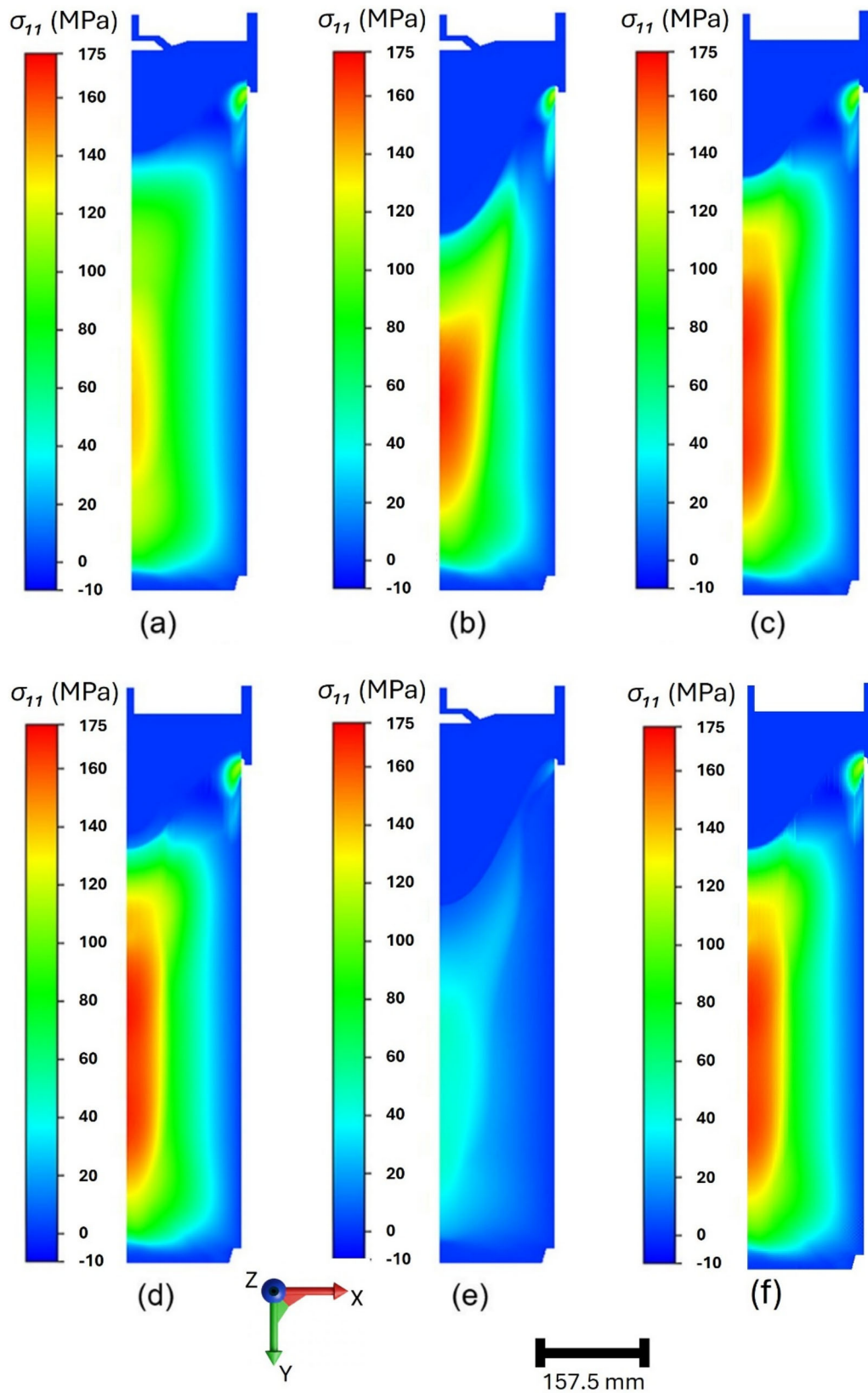
Figure 5 compares CCS values in the cross-section of the billets from different simulation cases. Figure 5a–c (representing Trials 1–3, respectively) show the results of the CCS calculation on simulations that utilize the semi-solid AA7050 database. To see the effect of the semi-solid material database towards the CC susceptibility estimation, the results of these trials were compared with the results of simulation cases that use the Al-2 wt.%

Table IV. Geometrical factor of different types of crack initiator defined the formulation of the CCS

Penny-shaped crack	Thumbnail-shaped crack
$a_c = \frac{\pi}{4} \left(\frac{K_{Ic}}{\sigma_{11}} \right)^2$	$a_c = \frac{\pi}{(2 \times 1.13)^2} \left(\frac{K_{Ic}}{\sigma_{11}} \right)^2$

a_c is half of CCS, K_{Ic} is plane strain fracture toughness, and σ_{11} is the first principal stress which is readily available from ALSIM calculation.

Sensitivity of a Multi-Physics DC Casting Model to Material Database Selection: Implications on Hot-Tearing and Cold-Cracking Prediction in an AA7050 Alloy



◀Fig. 2. Comparison of first principal stress calculations in different casting scenarios and materials databases. Simulation that uses complete AA7050 material databases: (a) Trial 1 – healthy case, (b) Trial 2 – CC case, and (c) Trial 3 – HT case; simulation that uses AA7050XTR on semi-solid database: (d) Trial 4 – HT case; the simulation that uses AA1050 at the fully-solid (hardening) part of the database: (e) Trial 5 – CC case; while the HT-case simulation that utilizes Al-2 wt.% Cu semi-solid database is (f) Trial 6. The scale bar (157.5 mm) represents the billet radius (half a diameter of the 315-mm billet). The axis triad indicates the coordinate orientation: X (radial), Y (casting direction), and Z (out-of-plane normal).

Cu semi-solid material database (Trial 6; Fig. 5f). From this comparison, the trend of the CCS value distribution was similar for each corresponding casting scenario between the two different semi-solid databases.

DISCUSSION

The results of this study demonstrate that ALSIM is sensitive to the choice of fully-solid (hardening) database. Substituting the AA7050 hardening data with those of AA1050, which is a soft, highly ductile alloy with a significantly lower strength,^{31,32} produces a marked reduction in predicted first principal stress and, ultimately, CCS measure. This outcome is physically consistent: softer materials accumulate less residual stress under equivalent thermal loading, and it further corroborates the well-established observation that CC typically occurs in high-strength (hard) aluminum alloys, such as the 2xxx and 7xxx series.^{6,18,19}

The insensitivity of CCS to semi-solid database selection can be understood from the thermal and stress history of the DC-cast billet, which was studied by Lalpoor et al.¹⁷ The dominant stress build-up in DC-cast AA7050 billets occurs after full solidification, driven by inhomogeneous thermal contraction in the fully-solid regime, with the maximum principal stress reaching its peak value at temperatures well below the solidus ($\sim 200^\circ\text{C}$). Stress levels during the semi-solid stage remain relatively low and do not significantly contribute to the final residual stress state, which governs the CCS. Therefore, the choice of a semi-solid database has little influence on the CCS outcome, and the fully-solid hardening database is the dominant factor controlling CCS predictions.

The most significant change in CCS occurs when the fully-solid (hardening) database is varied. Substituting AA1050 for AA7050 in the CC scenario (Trial 5; Fig. 5e versus Trial 2; Fig. 5b) reduces the peak first principal stress from 171 MPa to 47 MPa (-72.5%) and increases the minimum CCS from 2.4 mm to approximately 25 mm, which is an order-of-magnitude increase. This is also reflected visually, with the CC-susceptible region (i.e., the blue-colored area in Fig. 5) becoming significantly smaller in Trial 5 than in Trial 2. By comparison, varying only the semi-solid database from Al-2 wt.%

Cu to AA7050 or AA7050XTR, changes the peak first principal stress by less than 5 MPa across all corresponding scenarios and has no discernible effect on either ICS (steady-state ≈ 0.00025 ; Fig. 4) or CCS. Overall, these results confirm that the fully-solid database is the dominant factor governing CCS and stress predictions, while the semi-solid database mainly influences the distribution of local stress within the mushy zone without significantly affecting the macroscopic cracking indicators.

In contrast, varying the semi-solid material database produces negligible differences in both the predicted first principal stress and HT susceptibility (ICS), which requires further analysis given the substantial differences in constitutive parameters between the tested semi-solid databases. To understand this insensitivity, the mechanical response within the mushy zone was analyzed in detail between the rigidity point ($f_s = 0.85$) and the solidus ($f_s = 1.0$), i.e., in the solidification interval most associated with HT initiation.^{2,7} The HT casting scenario was selected as the representative case, as it yielded the highest ICS peak value across all the trials. As illustrated in Fig. 6, the analysis was performed along the billet centerline at the deepest part of the sump, traversing approximately 20 mm from $f_s = 0.85$ to $f_s = 1.0$.

Figure 7a reveals that the radial strain-rate profiles for all three semi-solid databases (Al-2 wt.% Cu, AA7050, and AA7050XTR) were nearly identical throughout the mushy zone, converging to the same value approaching the solidus. This is attributed to the displacement-controlled nature of the DC casting process: the strain field in the mushy zone is governed primarily by the imposed thermal contraction, which is determined by casting geometry, cooling conditions, and casting speed, rather than by the material's constitutive response. Conversely, Fig. 7b shows that the radial stress profiles did differentiate between databases, with AA7050XTR yielding significantly higher stress, consistent with its augmented cohesion parameters. However, this stress divergence only became appreciable very close to the solidus ($f_s > 0.97$), over a spatially narrow zone that contributed insufficiently to the ICS value.

This insensitivity holds across both extremes of the database range tested. Al-2 wt.% Cu, which is a weaker semi-solid material than AA7050²⁶ produced an ICS value essentially identical to that of AA7050 and AA7050XTR (Fig. 4). If weaker semi-solid properties were to increase ICS sensitivity, a measurable difference would be expected for Al-2 wt.% Cu compared to AA7050. The absence of such a difference confirms that ICS is fundamentally insensitive with respect to semi-solid material properties, regardless of whether the alloy in the database is weaker or stronger than the reference. This represents a fundamental limitation of strain-based HT criteria for alloy-to-alloy comparison.

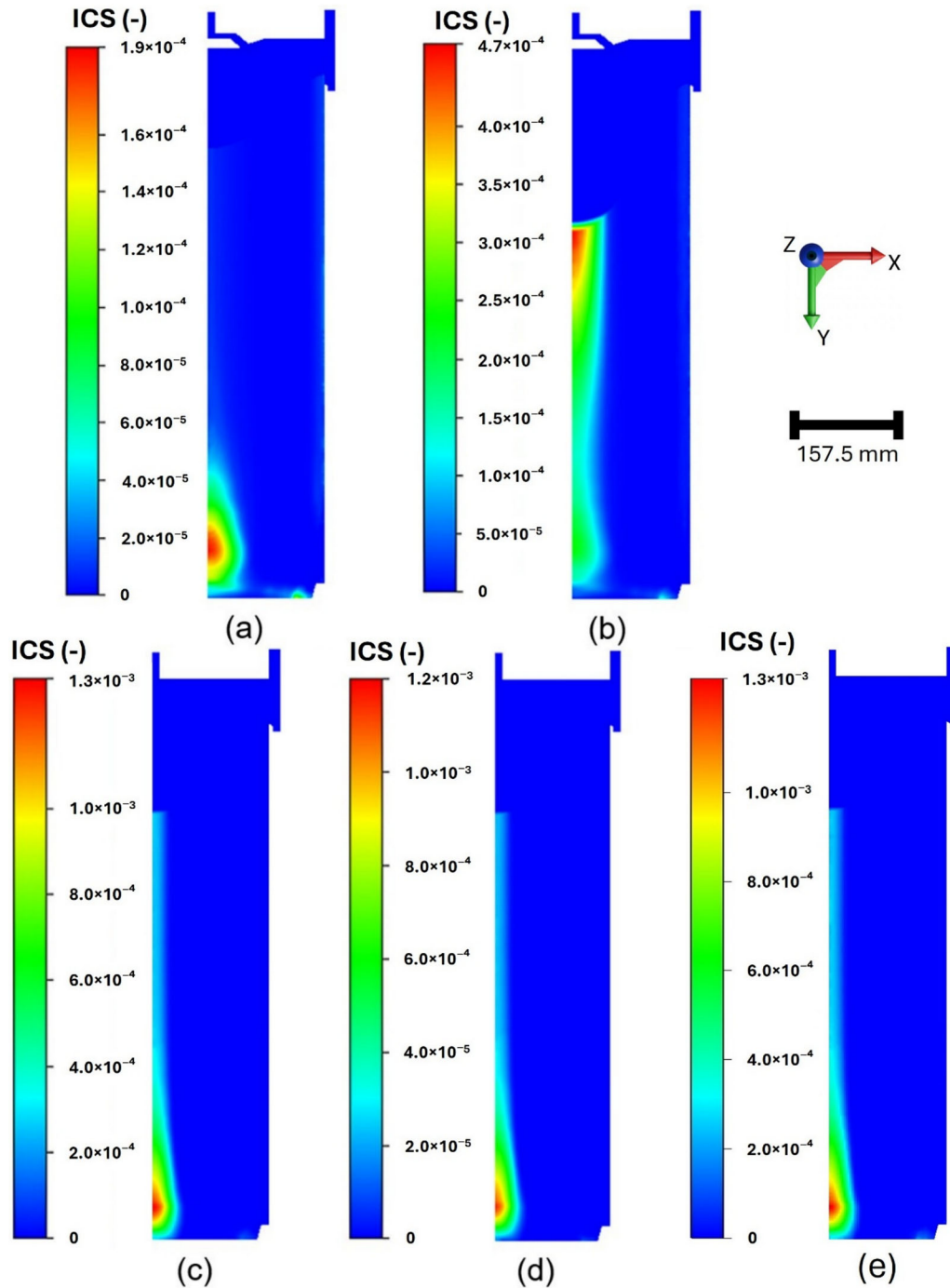


Fig. 3. Comparison of integrated critical strain (ICS) value in different casting scenarios and materials databases. Simulation that uses complete AA7050 materials databases: (a) Trial 1 – healthy case, (b) Trial 2 – CC case, and (c) Trial 3 – HT case. Simulations that use different semi-solid databases, both using the HT-case: (d) AA7050XTR – Trial 4, and (e) Al-2 wt.% Cu – Trial 6.²³ The scale bar (157.5 mm) represents the billet radius (half a diameter of the 315-mm billet). The axis triad indicates the coordinate orientation: X (radial), Y (casting direction), and Z (out-of-plane normal).

While for casting-parameter optimization, the ICS remains a useful relative indicator, for alloy-to-alloy comparison or alloy-development screening, a complementary criterion which is alloy-composition sensitive, like one of the criteria described in Eskin et al.⁷ is essential. The current ICS formulation would rank different alloys similarly if subjected to

the same casting conditions, which contradicts the well-known alloy-dependent nature of HT susceptibility.^{2,7,16}

Such a limitation does not reflect a deficiency in ALSIM's mechanical solver: as demonstrated by the stress responses in Fig. 7b, the model is responsive to different semi-solid material properties. Rather,

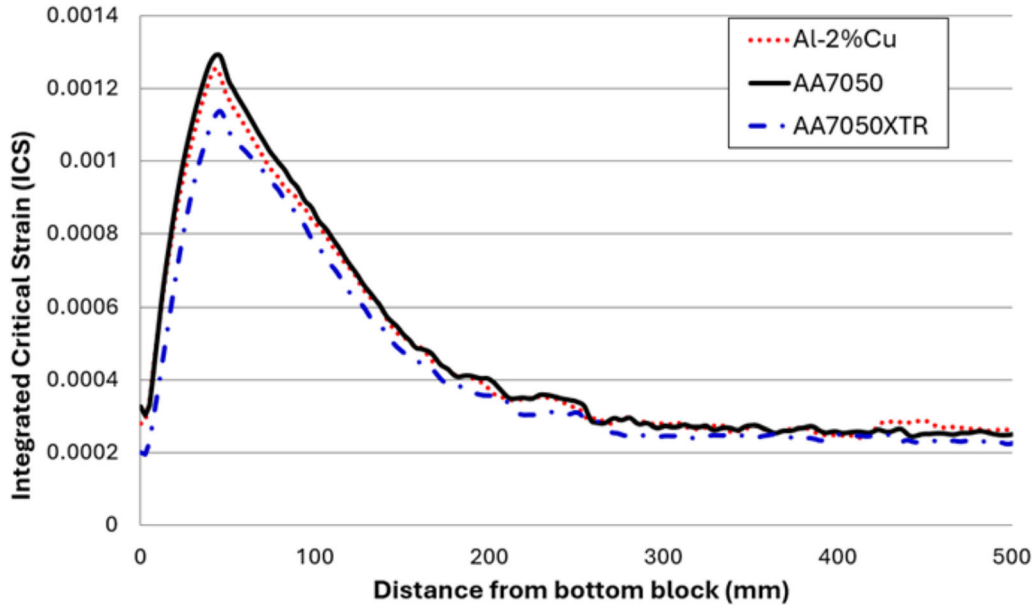


Fig. 4. Centerline ICS comparison for the HT scenario using AA7050 (Trial 3), AA7050XTR (Trial 4), and Al-2 wt.% Cu (Trial 6)²³ semi-solid databases. Plot from above bottom block to 500-mm cast length.

the limitation lies in the ICS formulation itself: by integrating a kinematic quantity (plastic strain rate), ICS captures the effect of process-parameter changes but discards the material-dependent stress information that has been properly calculated by the model. Therefore, to improve HT prediction accuracy, a complementary criterion that re-introduces material sensitivity into the susceptibility assessment is required.

Building on the strain-reserve concept introduced in the Introduction, HT susceptibility is quantified here using the improved RSV. RSV is defined as the difference between the alloy's semi-solid fracture strain, that can be measured experimentally as a function of solid fraction^{26,27,33} and the viscoplastic strain imposed by the casting process, which can be obtained directly from the ALSIM simulation output. This represents the major difference from earlier versions of this criterion, where either the thermal contraction accumulated in the solidification range or a measured elongation was used. When $RSV \leq 0$ at any location, the alloy has depleted its ductility reserve, and HT may form at that point. Unlike ICS, RSV is explicitly material-dependent: alloys with lower semi-solid ductility (such as AA7050 relative to Al-2 wt.% Cu) will reach $RSV = 0$ under moderate casting conditions, which agrees with industrial practice.

Magnin et al.³⁴ proposed a related form of the HT criterion, comparing the maximum principal viscoplastic strain from a DC-casting simulation against an experimentally measured semi-solid fracture-strain curve, providing a valuable means of identifying regions of elevated HT risk. The present work builds on this type of strain-based comparison by additionally benchmarking against

the HT-case scenario to identify a critical ICS value at which catastrophic HT was observed,²³ thereby providing a more direct quantitative link between the simulated field and the measured semi-solid fracture strain used in RSV. This allows the present criterion to move a step further toward predicting whether HT will occur, rather than primarily indicating where the risk is elevated.

As a proof-of-concept illustration of this framework, two experimentally based quantities are combined. The average engineering fracture strain from previously reported semi-solid tensile tests,²⁶ measured across the brittle solidification range ($f_s = 0.88\text{--}0.97$), gives $\varepsilon_f \approx 0.0084$. The maximum ICS predicted by ALSIM for the HT case (Trial 3), $ICS_{max} \approx 0.0013$, corresponds to the casting condition experimentally confirmed to produce catastrophic HT.²³ Basing the RSV framework on this experimentally validated HT event, i.e., requiring $RSV = 0$ at ICS_{max} , yields a localization factor $k = \varepsilon_f / ICS_{max} \approx 6.5$, where k links the element-averaged ICS to the strain concentrated in the intergranular liquid films where tearing initiates in semi-solid tensile samples.

A factor of this order is physically reasonable, given the difference in scale between the billet (simulated with 2.5×2.5 mm elements) and the semi-solid tensile specimen (with diameter of 11.68 mm) used to measure ε_f . This is consistent with the multi-phase nature of the semi-solid mush itself: rather than being a homogeneous continuum, it comprises a solid dendritic network, interdendritic liquid, and shrinkage/gas porosity, with failure governed by its weakest features, such as continuous liquid films, poorly fed regions, and pores acting as crack nuclei.¹⁵ The billet-scale mush

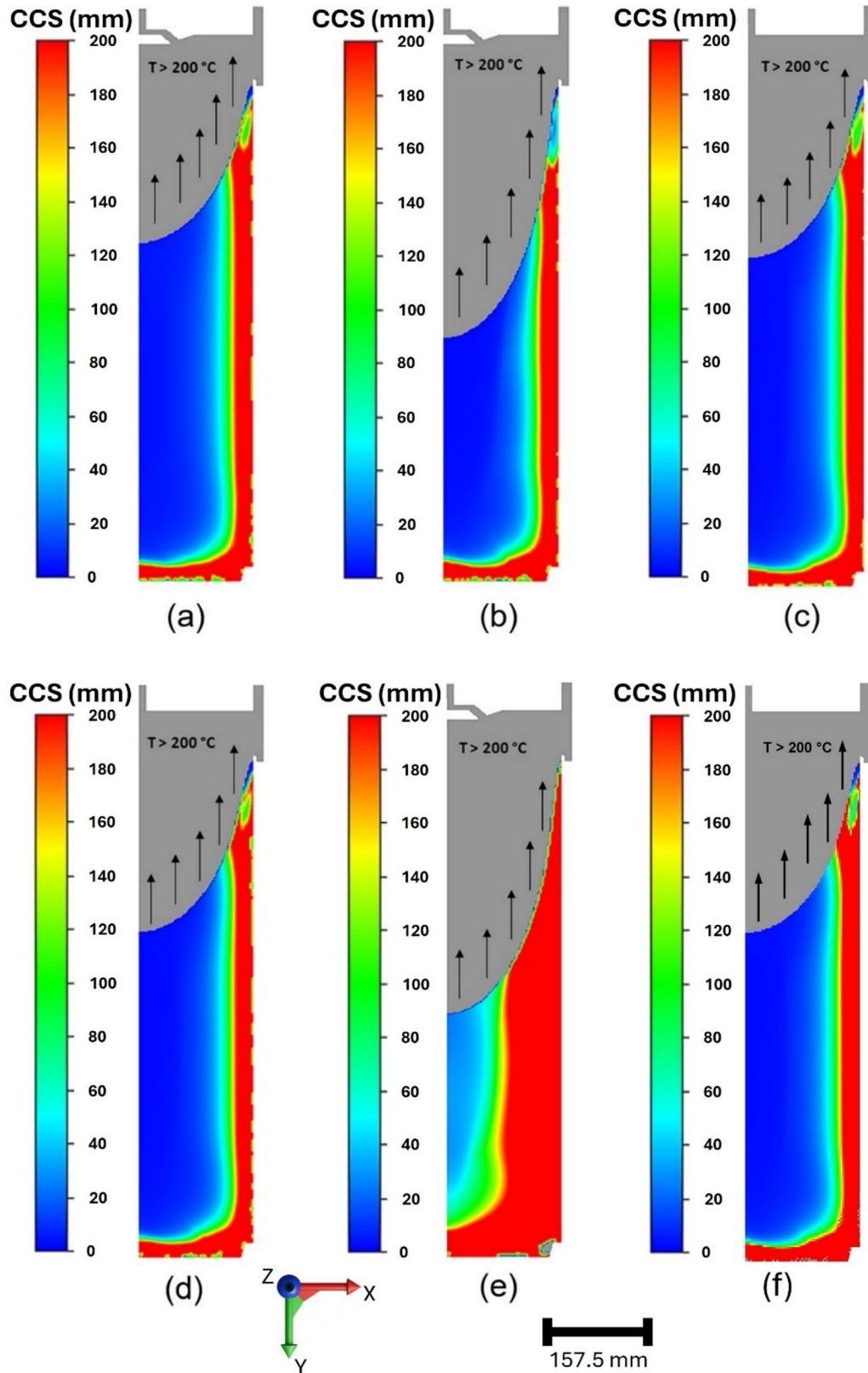


Fig. 5. Comparison of the CCS value in different casting scenarios and materials databases. Simulation that uses complete AA7050 materials databases: (a) Trial 1 – healthy case, (b) Trial 2 – CC case and (c) Trial 3 – HT case. Simulation that uses AA7050XTR on semi-solid database: (d) Trial 4 – HT case, the simulation that uses AA1050 at the fully-solid (hardening) part of the database; (e) Trial 5 – CC case, while the HT-case simulation that utilizes Al-2 wt.% Cu semi-solid database is (f) Trial 6. The scale bar (157.5 mm) represents the billet radius (half a diameter of the 315-mm billet). The axis triad indicates the coordinate orientation: X (radial), Y (casting direction), and Z (out-of-plane normal).

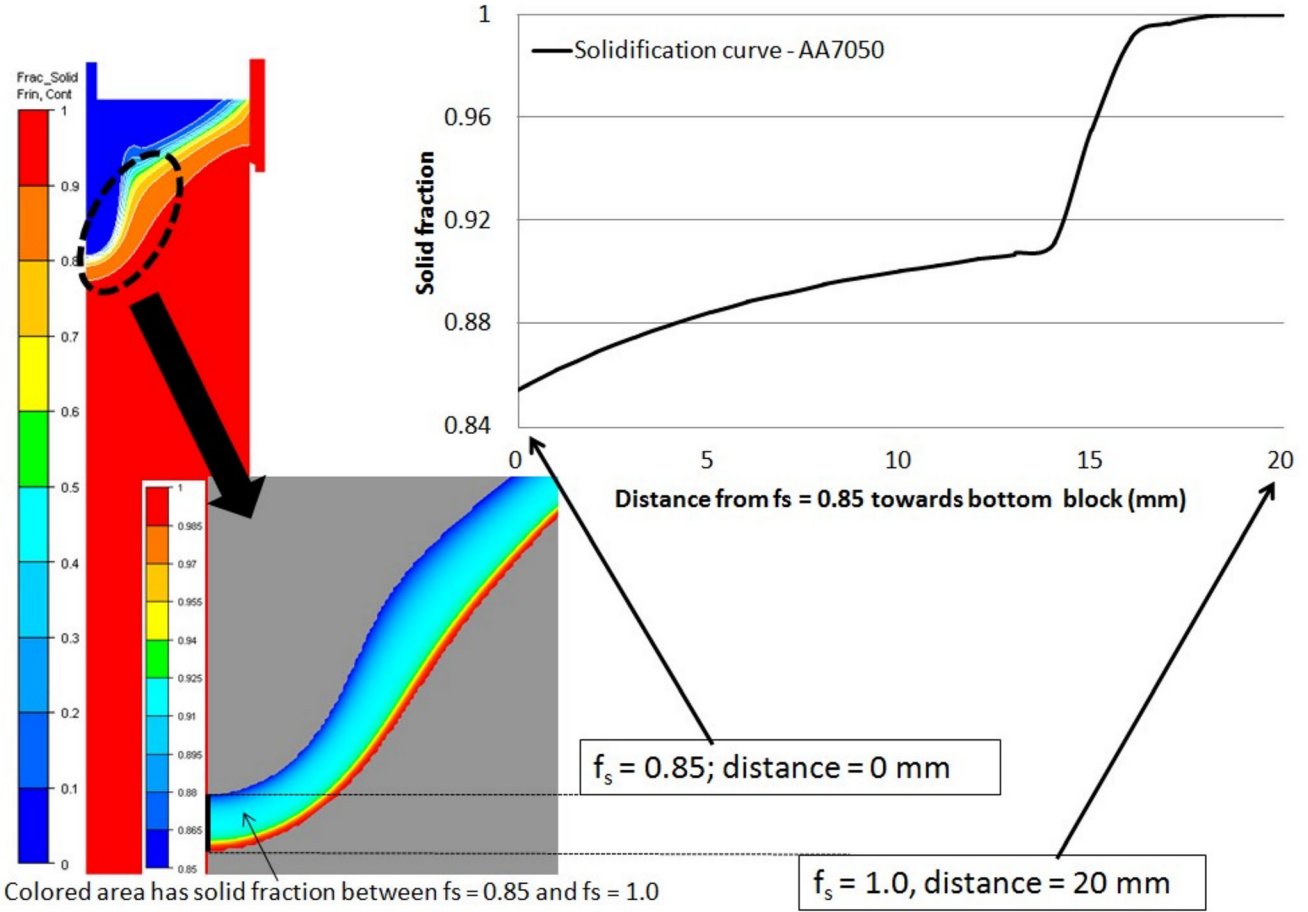


Fig. 6. Detailed analysis at the lower part of the mushy zone of an AA7050 alloy during DC casting.

is therefore expected to reflect more severe, more widely distributed defects than the small, more uniformly cooled tensile specimen. This is further supported by previous work showing that the billet centerline experiences the lowest mushy-zone pressure during solidification,²³ consistent with the feeding difficulty and porosity reported at the billet center in DC-cast Al-Cu alloys^{35,36} and with observed HT concentration in the central part of DC-cast billets.¹⁶ This direction is also broadly consistent, as an analogy, with the classical weakest-link principle,³⁷ whereby the probability that a volume contains a critical flaw increases with the number of potential flaw sites it contains. It should be emphasized, however, that, with only a single calibration point and k being fitted rather than independently predicted, the present example should be regarded as a first estimate to be refined and tested against additional casting/test pairs, rather than a validated material constant.

Since RSV identifies whether and where HT initiates within the billet, it also enables estimation of the HT zone geometry: the spatial extent of the $RSV \leq 0$ region provides an approximate crack length that can be directly compared against the local CCS value. If this estimated HT length exceeds

the CCS, the micro-HT is large enough to trigger catastrophic CC upon further cooling. This suggests a possible route toward closing the conceptual loop between the two crack types, addressing a gap identified by Eskin and Katgerman¹⁵ and providing a framework for unified HT-CC prediction. Figure 8 illustrates a potential implementation of this approach within the ALSIM simulation domain.

The present results strengthen the case for the micro-HT $\rightarrow$ CC connection mechanism. In the CC casting scenario (Trial 2; Fig. 3b), the steady-state ICS is significant ($\sim 5 \times 10^{-4}$), indicating that the high casting speed promotes conditions favorable to micro-HT formation, even in the absence of a catastrophic HT. Simultaneously, the deep sump (254 mm) and high thermal gradient produce elevated residual stresses and the lowest CCS values among all scenarios. The combination of (1) micro-HT as potential pre-existing defects and (2) high residual stresses in a material that is brittle below $\sim 300^\circ\text{C}$ ¹⁷ creates the conditions for catastrophic CC, which has indeed been the experimental outcome from the CC case.²³

This interpretation is further supported by the fracture-surface observations of Lalpoor et al.,¹⁷ who identified both interdendritic (HT-

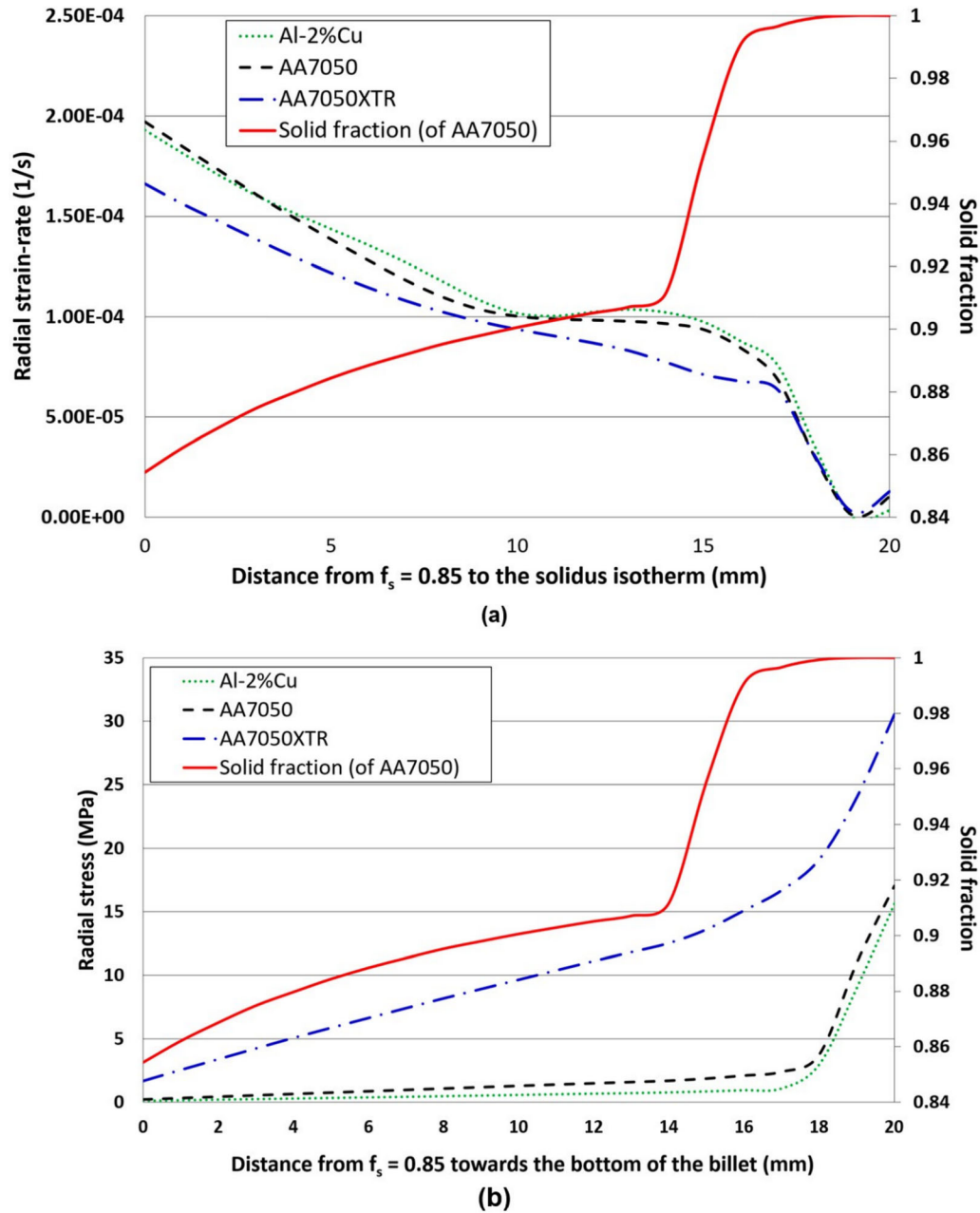


Fig. 7. (a) Plot of radial strain-rate from HT simulations with different semi-solid materials databases (Al-2 wt.% Cu,²³ AA7050 – Trial 3 and AA7050XTR – Trial 4) compared to the respective solid fraction at different positions in the sump. (b) Plot of radial stress from HT simulations with different semi-solid mechanical properties (Al-2 wt.% Cu,²³ AA7050 – Trial 3 and AA7050XTR – Trial 4) compared to the respective solid fraction at different positions in the sump.

characteristic) and transgranular (CC-characteristic) features on AA7050 CC fracture-surfaces, as well as inclusions at CC initiation points.¹³ Overall, these observations suggest that multiple solidification defect types, such as micro-HT, porosity, and inclusions, can serve as CC initiators, and that the critical factor is whether any of these defects exceed the local CCS at the temperature where the alloy becomes brittle. It should be noted, however, that,

while the present results are consistent with the hypothesis that micro-HT or other solidification defects may act as initiators for subsequent CC, they do not provide direct proof of a causal micro-HT to CC transition. The RSV-CCS framework proposed here should, therefore, be seen as a physics-based modeling concept, and further experimental validation will be needed before it can be applied as a predictive tool.

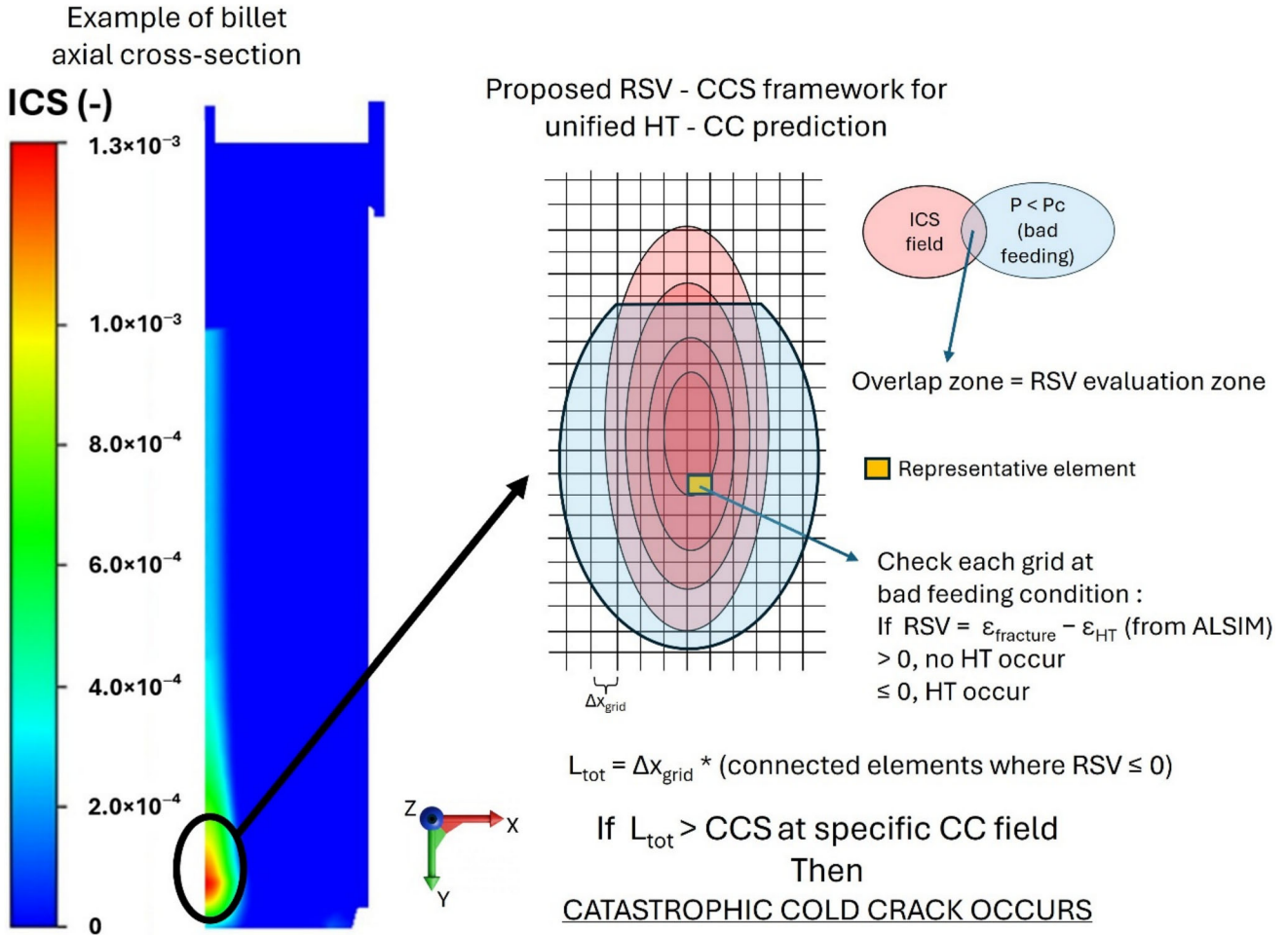


Fig. 8. Schematic of the proposed RSV-CCS framework for unified HT-CC prediction in DC casting.

The findings of this study have direct practical implications for simulation setup when characterizing new alloys. Capturing the full HT-CC connection requires sensitivity to both databases: the semi-solid database determines whether and where micro-HT forms (assessed via RSV), while the fully-solid database determines whether residual stresses are sufficient to propagate these defects into catastrophic CC (assessed via CCS). This combination motivates the following hierarchy for database development for new alloys, as follows:

Priority 1 – Fully-solid (hardening) database: This is the most critical input for accurate prediction of the overall stress field, residual stresses, and CC susceptibility. Substitution with a different alloy family, as illustrated by the AA1050 case, can lead to significant errors in peak stress and, thus, fundamentally incorrect CC risk assessments. For any new high-strength alloy intended for DC casting, this database should be obtained first.

Priority 2 – Semi-solid database (non-HT-sensitive conditions): For alloys and casting setups

where HT is not the primary concern, the incumbent semi-solid database from the same alloy family provides adequate accuracy. In this study, the Al-2 wt.% Cu database produced global stress result variations within 5 MPa, and resulted in essentially identical ICS and CCS values compared to the dedicated AA7050 database. This substitution can save significant characterization time and costs, as semi-solid rheological testing requires specialized equipment and is experimentally challenging.^{24,25,33,38}

Priority 3 – Semi-solid database (HT-sensitive conditions): When the alloy to be developed is HT-sensitive, the strain-based ICS alone is insufficient for alloy discrimination. In this case, an alloy-specific semi-solid database combined with an additional criterion such as RSV is needed. The investment in semi-solid characterization is then justified by improved prediction capability, particularly for screening new alloy compositions during alloy development.

CONCLUSION

This work has examined the sensitivity of ALSIM DC-casting crack-susceptibility predictions to material database selection for 315-mm-diameter AA7050 billets cast under healthy, HT, and CC casting conditions. The following conclusions can be drawn:

1. The predicted CC susceptibility is strongly influenced by the fully-solid hardening database. This is observed when the AA7050 hardening database was replaced by the softer AA1050 database under the same CC casting condition; the predicted first principal stress decreased and the minimum CCS increased, indicating a lower predicted risk of CC. This confirms the importance of alloy-specific fully-solid mechanical data for reliable CCS-based assessment.
2. The influence of the semi-solid database selection on the global stress field, ICS distribution and CCS values was much weaker for the cases examined in this study, even the artificial AA7050XTR database, which was introduced as an exaggerated sensitivity test, led to only limited changes in ICS relative to the AA7050 and Al-2 wt.% Cu semi-solid databases. Although the local mushy-zone stress response was sensitive to the semi-solid database, this sensitivity was not strongly captured by the strain-based ICS indicator.
3. The low sensitivity of ICS to the different semi-solid databases used indicates that the mushy-zone strain accumulated during the current AA7050 DC-casting conditions is primarily determined by thermal contraction imposed by the process and displacement compatibility; therefore, ICS remains a useful relative process indicator for comparing different casting conditions within the same modeling framework. However, direct alloy-to-alloy comparisons based solely on ICS values should be interpreted carefully, unless both alloy-specific ductility and the impact of the chosen semi-solid database on material response are considered.
4. A modified RSV concept is proposed as a complementary material-sensitive indicator for future HT evaluation. By comparing the process-imposed mushy-zone strain with the measured semi-solid fracture strain, RSV provides a possible route for the inclusion of alloy ductility in HT prediction, and thus may offer an indication of whether HT has initiated. Coupling RSV-based estimates of potential HT initiation zones with local CCS values may also contribute to the future development of an integrated HT-CC assessment framework, although further experimental verification is still needed to establish this relationship.

ACKNOWLEDGEMENTS

This research was carried out under Project Number M42.5.09340 of the research program of the Materials innovation institute, M2i, The Netherlands (www.m2i.nl). The authors thank Tata Steel R&D (IJmuiden, The Netherlands) for providing casting trial data and Mr. Dag Mortensen of the Institute for Energy Technology (IFE, Norway) for ALSIM software support and development collaboration.

FUNDING

Materials innovation institute, M2i, M42.5.09340, Dmitry G. Eskin.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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