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Comprehensive Modeling of Major (Cu) and Minor (Sr) Alloying Elements Impact on the Crack Susceptibility Coefficient of Cast Hypoeutectic AlSi6Cu(1–4 wt.%) Alloys

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Abstract

This paper briefly overviews factors influencing hot tearing in hypoeutectic Al–Si–Cu cast alloys. Four base alloys, AlSi6Cu1, AlSi6Cu2, AlSi6Cu3, and AlSi6Cu4, were studied to analyze the impact of varying Cu content on hot tearing formation. The effect of Sr as a modifier on the hot tear formation was also examined. Cooling curve analysis (CCA) was employed to collect essential data, including dendrite coherency and rigidity temperatures and the corresponding solid fraction at each characteristic solidification temperature. A novel analytical model for predicting the crack susceptibility coefficient (CSC) is proposed. This model builds upon the previously established CSC model by Clyne and Davies, incorporating critical time/temperature periods between dendrite coherency and rigidity temperatures. The CSC calculated applying a novel analytical method based on temperature criteria has been additionally compared to an experiment-based hot cracking indexing (HCI) method using experiment data for the following three alloys: AlSi7Mg0.1Cu0.05, AlSi7Mg0.3Cu0.05, and AlSi7Mg0.6Cu0.05, taken from literature. The results indicate a good correlation between theoretical models and the experimental HCI method. The new model is particularly valuable for industrial applications as it provides flexibility by allowing both time-based and temperature-based calculations. It precisely captures the critical period during solidification where hot tearing is most likely to occur while accounting for varying cooling rates and their effect on time intervals between critical points. The model considers temperature-dependent behavior during the vulnerable period and incorporates the alloy composition's influence on coherency and rigidity temperatures.

Keywords Hot tearing · Crack susceptibility coefficient · Copper · Strontium · Thermal analysis

1 Introduction

The Al – Si – Cu hypoeutectic alloys dominate the automotive industry, particularly in producing complex components like cylinder heads and engine blocks. This status arrives from their superior castability and mechanical performance. These alloys' microstructural and mechanical properties are primarily determined by two distinct eutectic systems: Al – Si and Al – Si – Cu [1–4]. A comprehensive understanding of these alloys' solidification paths is paramount for metallurgical engineers. One of the problems that can occur during the production of these parts using Al – Si – Cu cast hypoeutectic alloys is hot tearing. Hot tearing is a critical defect in metal casting, particularly in aluminum alloys, where the liquid metal solidifies and cracks under stress [5]. Figure 1 shows typical micrographs of hot tearing in a restrained rod-like test sample produced using the AlCu4.55 alloy [5]. These cracks typically follow intergranular paths and exhibit a dendritic morphology [5, 6]. When hot tearing occurs, the casting parts often require repair or complete disposal, resulting in substantial losses for casting plants. Understanding the variables influencing hot tearing is essential for optimizing casting processes and enhancing the quality of the final product. Key factors such as alloy composition, processing parameters, and microstructural characteristics are crucial for optimizing the performance and

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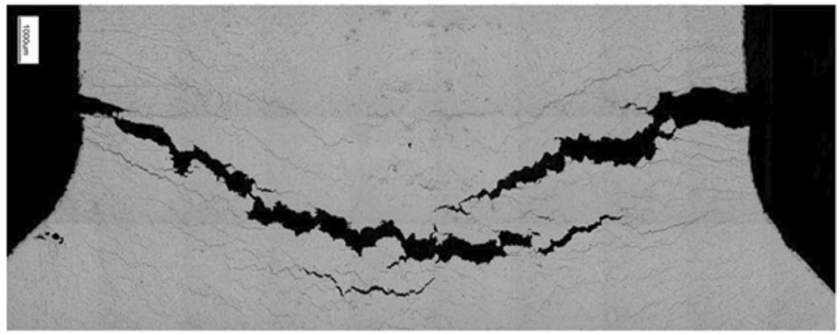

Fig. 1 Micrographs showing hot tears in the neck region of AlCu4.55 alloy [5]

quality of castings, as they directly influence the susceptibility to defects like hot tearing and ultimately affect the mechanical properties and integrity of the final product. The impact of the alloy composition can be attributed to the alloy's freezing range: broader freezing ranges generally lead to higher susceptibility to hot tearing [5, 7]. Eutectic phases within the alloy also play a significant role in hot tearing [8]. During the later stages of solidification, the eutectic can either worsen or mitigate hot tearing, depending on its quantity. A limited amount of the eutectic can increase susceptibility, while excess may lead to improved feeding characteristics, thereby reducing cracks. Finally, the grain structure of the alloy, influenced by both composition and processing, affects hot tearing. Fine equiaxed grains are generally preferred, as they better accommodate local strains [8, 9]. However, excessive grain refinement can paradoxically increase susceptibility due to reduced permeability in the mushy zone, as shown in studies by Easton et al. and others [8, 10]. Optimal grain morphology is crucial; columnar grains are associated with higher tearing rates than equiaxed structures. In addition to the influence of alloy chemistry on hot tearing in aluminum alloys, the effects of processing conditions also deserve consideration. The pouring temperature significantly impacts hot tearing. While some studies suggest that higher superheat can reduce the likelihood of hot tearing by spreading thermal gradients, others indicate that elevated temperatures can exacerbate cracking by promoting columnar grain growth [11]. The relationship between superheat, alloy composition, and cracking susceptibility is complex and often dependent on the specific alloy system and casting conditions. Mold temperature directly affects the cooling rate and solidification pattern, thus influencing hot tearing [12]. Research indicates that higher mold temperatures typically reduce cracking severity. At elevated temperatures [13], the coarser microstructure allows for better liquid refilling and healing of cracks, enhancing the overall integrity of the casting. A comprehensive understanding of these metallurgical factors is essential for developing reliable casting processes, ensuring product quality, and minimizing manufacturing defects. This study investigates the influence of Cu (a major alloying element) and Sr (a modifying alloying element) on hot tearing susceptibility in hypoeutectic AlSi6Cu alloys with Cu content ranging from 1 to 4 wt.%. Furthermore, this research seeks to refine existing mathematical analytical models for predicting the relationship between chemical composition and hot tearing formation by AlSiCu cast alloys.

1.1 Hot Tearing Non-mechanical Predictive Models

Previous studies have established various predictive models to enhance aluminum casting operations [14–25]. A review of the literature reveals that crack susceptibility characterization methods [14] can be categorized into three fundamental approaches based on mechanical properties:

- Stress-based criteria [15–17]
- Strain-based criteria [15, 18, 19]
- Strain-rate-based criteria [20–23]

Apart from the mechanical aspects, several mathematical models in the literature can be used to predict the impact of chemistry on the development of hot tearing [20, 24–28]. The most used is the non-mechanical CSC model from Clyne and Davies [26].

As Fig. 2 illustrates, the CSC model correlates the susceptibility-composition relationship based on the consideration of the time during which the processes related to the crack formation can take place and when the structure is most vulnerable to cracking (critical time interval during solidification).

The *CSC* is defined as Eq. (1):

$$CSC = \frac{t_V}{t_R} = \left(t_{0.99} - t_{0.9}\right) / \left(t_{0.9} - t_{0.4}\right) \tag{1}$$

where:

- t_V is the vulnerable time, calculated as the time difference between mass fractions of liquid at 10% and 1%, and
- t_R is the time available for stress relief processes, calculated as the time difference between mass fractions of liquid at 60% and 10%.

Where $t_{0.99}$ is the time when the volume fraction of a solid (f_s) is 0.99, $t_{0.9}$ is the time when f_s is 0.9, and $t_{0.4}$ is the time when f_s is 0.4.

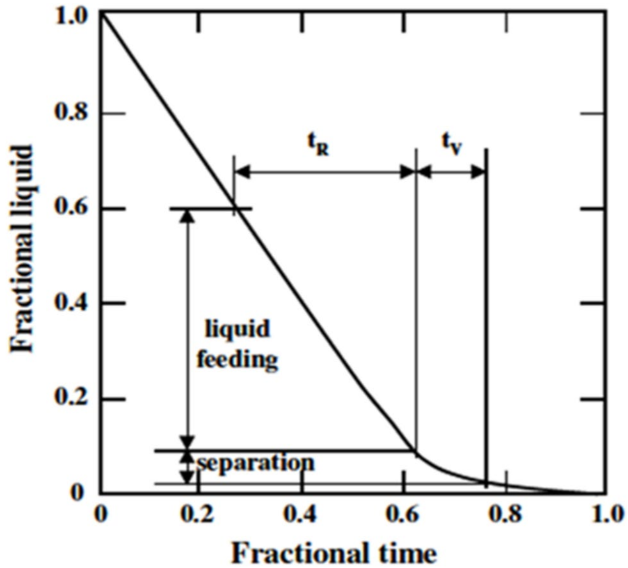

Fig. 2 Relationship between liquid fraction, recovery duration (t_R), and vulnerability duration (t_V)

Theories do not strongly support the criteria of the solid fraction, but in addition to the relatively simple concept and ease of the calculation, the experimental results were often reasonably explained with this model [29]. Since the Clyne–Davies model is relatively simple and based on many assumptions, some modified models have been suggested in available literature [24, 25, 27].

Katgerman [24, 25] and Kamga et al. [27] significantly improved the original Clyne and Davies model for predicting crack susceptibility. Katgerman [24, 25] updated Clyne and Davies's expression by introducing dendrite coherency time (the temperature at which the dendrite network begins to form) as follows Eq. (2):

$$CSC = \left(t_{99} - t_{cr}\right) / \left(t_{cr} - t_{coh}\right) \tag{2}$$

where t_{coh} is the time when the solid fraction is at the coherency point, t_{cr} is the time when feeding becomes inadequate, and t_{99} is the time when the solid fraction volume is 0.99.

Katgerman enhanced the Clyne and Davies solidification model by establishing more precise definitions of critical solid fraction ranges, specifically focusing on the period between $f_s = 0.85$ and 0.99, where the hot tearing risk is highest due to inadequate interdendritic feeding.

Kamga et al. [27] improved the hot tearing model by establishing a more comprehensive relationship between temperature and solid fraction. Their enhancement incorporated temperature-dependent parameters and introduced a detailed chronological analysis through the *CSC* in Eq. (3):

$$CSC = \left(T_{cr} - T_{0.01}\right) / \left(T_{coh} - T_{cr}\right) \tag{3}$$

In this equation, T_{coh} represents the dendrite coherency temperature, T_{cr} denotes the temperature at which feeding becomes inadequate, and $T_{0.01}$ corresponds to the temperature at 1% residual liquid ($f_s \approx 0.99$).

The model examines two critical temperature intervals. The first interval ($T_{cr} - T_{0.01}$) represents the vulnerable period between coherency temperature and near-complete solidification ($f_s \approx 0.99$). The second interval ($T_{coh} - T_{cr}$) defines the temperature range where stress relief occurs through mass feeding, typically between 0.40 and 0.99 of solid fraction. This formulation quantitatively measures hot tearing susceptibility based on the relative duration of these critical solidification periods.

2 Experimental Procedures

2.1 Material

Four Al – Si – Cu alloys with the chemical compositions presented in Table 1 are melted under standard laboratory conditions. The major alloying elements ranged from 5.78 to 5.91 wt.% Si and 1.07 to 3.96 wt.% Cu, while other alloying elements were kept to minimum levels. Each of these four base alloys was then used to create a second variant alloy by adding Sr to achieve a concentration of 140 ppm, resulting in a total of eight different alloys (four without Sr and four with Sr). All alloys were melted in an electric resistance furnace, under a protective nitrogen atmosphere to prevent hydrogen and oxygen contamination. Their chemical compositions have been determined using optical emission spectroscopy (OES).

2.2 Thermal Analysis Procedure

Thermal analysis (TA) was performed using samples of approximately 250 g from the remelted alloys poured into

Table 1 Actual chemical composition (in wt. %) of synthetic AlSiCu alloys

Alloy	Si	Cu	Fe	Mg	Mn	Zn
AlSi6Cu1	5.91	1.07	0.07	0.14	0.01	0.01
AlSi6Cu2	5.90	1.83	0.11	0.15	0.01	0.01
AlSi6Cu3	5.82	3.03	0.06	0.15	0.01	0.01
AlSi6Cu4	5.78	3.96	0.07	0.13	0.01	0.01

steel test cups. The cups were 60 mm high, with bottom and top diameters of 45 mm and 55 mm, respectively. Temperature measurements between 700 and 400 °C were recorded using two K-type thermocouples inserted into the melt. Data was acquired using a National Instruments system connected to a personal computer. For consistency, the thermocouple tips were positioned 15 mm from the cup bottom throughout all measurements. All experiments maintained constant cooling conditions with an approximate rate of 0.15 °C/s. This cooling rate was calculated as the ratio between the liquidus-to-solidus temperature difference and the total solidification time. Each of the TAs was duplicated to ensure reproducibility, yielding eight test samples. The Newtonian method was employed to determine the cooling curve baselines, which were then used to calculate the solid fraction distribution between liquidus and solidus temperatures.

3 Results and Discussion

In Section 1, several analytical expressions have been developed to predict the CSC in cast aluminum alloys, combining theoretical understanding with empirical observations. Mathematical models exhibit varying levels of accuracy when compared to experimental data, with their effectiveness influenced by multiple factors. These factors include alloy composition variations, casting conditions (such as cooling rates), and microstructural features, which can significantly impact the model's predictive capabilities. Modern research is advancing toward more sophisticated predictive models that incorporate additional parameters, such as dendrite coherency and rigidity temperatures, as a function of new alloy compositions and casting conditions. Recently, Djurdjevic et al. [30] further enhanced the understanding of hot tearing susceptibility by developing a modified approach to CSC calculation that incorporates both dendrite coherency and rigidity temperatures. This improved (altered) model considers the critical periods between these essential solidification points, expressing Eq. (4):

$$\mathrm{CSC} = \left(t_{0.99} - t_{\mathrm{Rigidty}}\right)/\left(t_{\mathrm{Rigidity}} - t_{\mathrm{DCT}}\right) \quad (4)$$

where $t_{0.99}$ is the time at 0.99 solid fraction, t_{DCT} is the time at the dendrite coherency temperature (DCT), and t_{Rigidity} is the time at the rigidity temperature.

The model can also be expressed in terms of temperature intervals as Eq. (5):

$$\mathrm{CSC} = \left(T_{0.99} - T_{\mathrm{Rigidity}}\right)/\left(T_{\mathrm{Rigidity}} - T_{\mathrm{DCT}}\right) \quad (5)$$

where $T_{0.99}$ is the temperature at 0.99 solid fraction, T_{DCT} is the temperature at the DCT, and T_{Rigidty} is the temperature at the rigidity temperature. The DCT represents the temperature (T_{DCT}) at which dendrites first form a coherent network, typically occurring at solid fraction values of 0.50 – 0.65. The rigidity temperature (rigidity), occurring at higher solid fraction values (0.85 – 0.95), marks the temperature (T_{Rigidity}) at which the alloy develops sufficient strength to resist deformation.

The parameters in Eqs. (4) and (5) were determined through TA data, including cooling curves, ΔT curves, and solid fraction curves. Time, being an intensive parameter, is highly sensitive to the mass of TA test samples, which often varies between experiments. Even small variations in sample mass can significantly affect the solidification times used in Eq. (4). Therefore, this study implements Eq. (5), which uses characteristic temperatures rather than times to better define the investigated alloys' CSC. Temperature is an extensive parameter and remains independent of sample mass. Regardless of sample weight, the measured temperature remains constant, varying only with the accuracy of the thermocouple used. Equation (5) precisely captures the critical period during solidification where hot tearing is most likely while accounting for varying cooling rates and their effect on time intervals between critical points. The model considers the temperature-dependent behavior during the vulnerable period and incorporates the influence of alloy composition on coherency and rigidity temperatures. The proposed model expressed in terms of temperature intervals effectively mitigates the solidification path of cast aluminum alloys.

According to Campbell [6], five feeding mechanisms (liquid, mass, interdendritic, burst, and solid feedings) occur during the solidification of cast aluminum alloys. The liquid and mass feedings, which occur at the beginning of the solidification process, are uncomplicated due to the low melt viscosity, a wide active feeding path, and relatively high melt temperature. The number of dendrites, which begin to develop immediately after the liquidus temperature is reached, is not yet sufficient to slow down melt movement. As the melt temperature decreases during the further solidification process, those growing dendrites begin to impinge on each other, forming a coherent dendritic network that slows down the remaining melt flow. The temperature at which this happens is called the dendrite coherency temperature (DCT). This temperature marks the transition from mass to interdendritic feeding regions in cast aluminum alloys. Further solidification decreases the liquid fraction, and the stress is spread over larger distances through the rigid solid skeleton.

Additionally, according to Campbell [6], the stress will exceed the strength at the rigidity temperature, resulting in the breakdown of the solid dendritic skeleton. The rigidity temperature marks the point at which interdendritic feeding stops and burst feeding begins. Solid feeding starts at the solidus temperature when the last melt drop

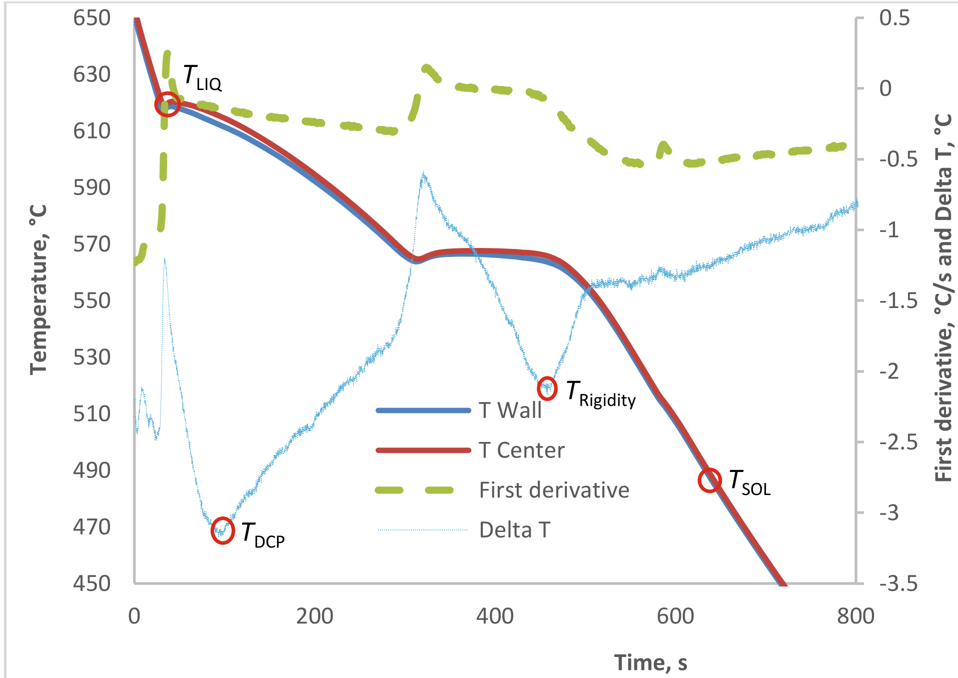

Fig. 3 Characteristic solidification temperature was determined using the cooling curves (TC), first derivative TC curve, and ΔT curve ($T_w - T_c$) for AlSi6Cu4 alloy

is transformed into a solid. Therefore, the selected characteristic solidification temperatures (DCT and rigidity) from Eqs. (4) and (5) can be used to describe the recovery and vulnerable feeding duration.

The simplicity of the proposed novel-modified analytical model for the prediction of the CSC can be recognized in the fact that all input solidification parameters are needed for Eqs. (4) and (5) can be obtained from the cooling curve. As shown in Fig. 3, all characteristic solidification temperatures were determined using cooling curves, their first derivatives, and temperature difference curves (ΔT). The dendrite coherency temperature (T_{DCT}) and rigidity temperature ($T_{Rigidity}$), along with their corresponding times, were identified from the temperature difference curve ($\Delta T = T_w - T_c$),

Table 2 Characteristic solidification temperatures and corresponding solid fractions in AlSi6Cu(1 – 4) alloys were determined using the CCA

Alloy	$T_{@DCP}$, °C	$f_{S,@DCP}$, %	$T_{@Rigidity}$, °C	$f_{S,@Rigidity}$, %
AlSi6Cu1	614.75	20.75	569.18	85.02
AlSi6Cu2	613.01	15.24	568.46	74.23
AlSi6Cu3	611.3	13.9	565.8	68.32
AlSi6Cu4	605.16	12.14	562.23	66.14
AlSi6Cu1 Sr140	615.4	17.32	565.75	89.54
AlSi6Cu2Sr 140	612.62	16.37	559.55	87.05
AlSi6Cu3 Sr 140	607.8	15.85	557.85	82.81
AlSi6Cu4 Sr 140	606.1	13.16	554.1	68.17

where T_w and T_c represent the wall and center temperatures, respectively.

Table 2 presents the investigated alloys' characteristic solidification temperatures and corresponding solid fraction values. The solid fraction values at dendrite coherency and rigidity temperatures were calculated using the Newtonian approach [31].

As can be seen from Table 2 and Fig. 4, any increase in the content of Cu from 1.07 to 3.96 wt.% depresses the DCT and Rigidity temperatures. The addition of 2.89 wt.% of Cu reduced the DCT temperature from 614.75 to 605.16 °C, as well as rigidity temperature from 569.18 to 562.23 °C.

The temperature difference between the DCT and rigidity temperature ($T_{DCT} - T_{Rigidity}$) marks the most critical period for hot tear formation. During this phase, the semi-solid material possesses enough strength to transmit stress but lacks sufficient ductility to accommodate strain without cracking.

Foundry experience has shown that higher Cu content in Al–Si cast alloys increases their susceptibility to hot cracking. Figure 5 supports this observation, indicating that adding Cu to cast AlSi6 alloys increases the CSC from 1.1 to 1.44, making the alloys more prone to hot tearing.

According to Fig. 5, the addition of strontium (Sr) to aluminum alloys with varying copper contents demonstrates a significant beneficial effect on reducing the cracking susceptibility coefficient (CSC). The CSC decreases from 0.94 in AlSi6Cu1 alloys to 0.69 in AlSi6Cu4 alloys, indicating improved resistance to hot cracking. This improvement stems primarily from Sr's ability to modify silicon

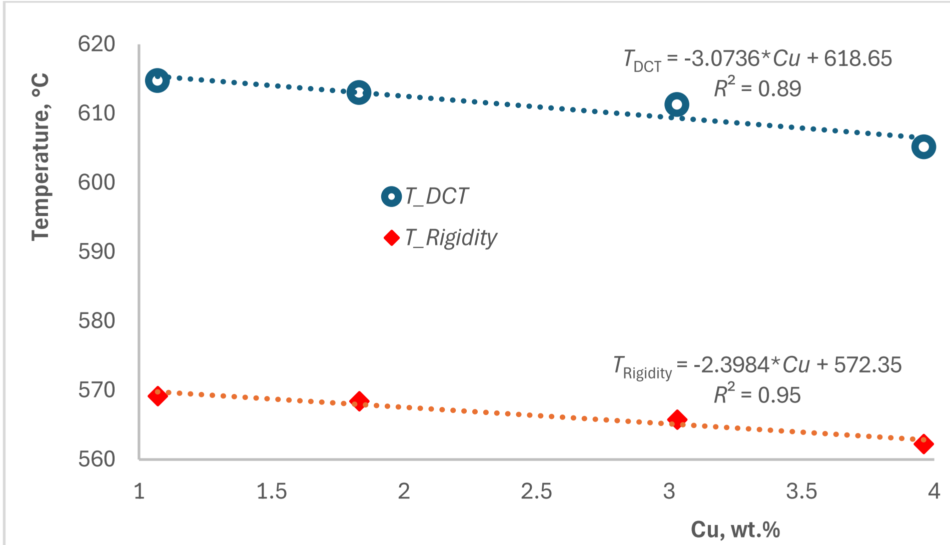

Fig. 4 Impact of Cu on DCT and rigidity temperatures

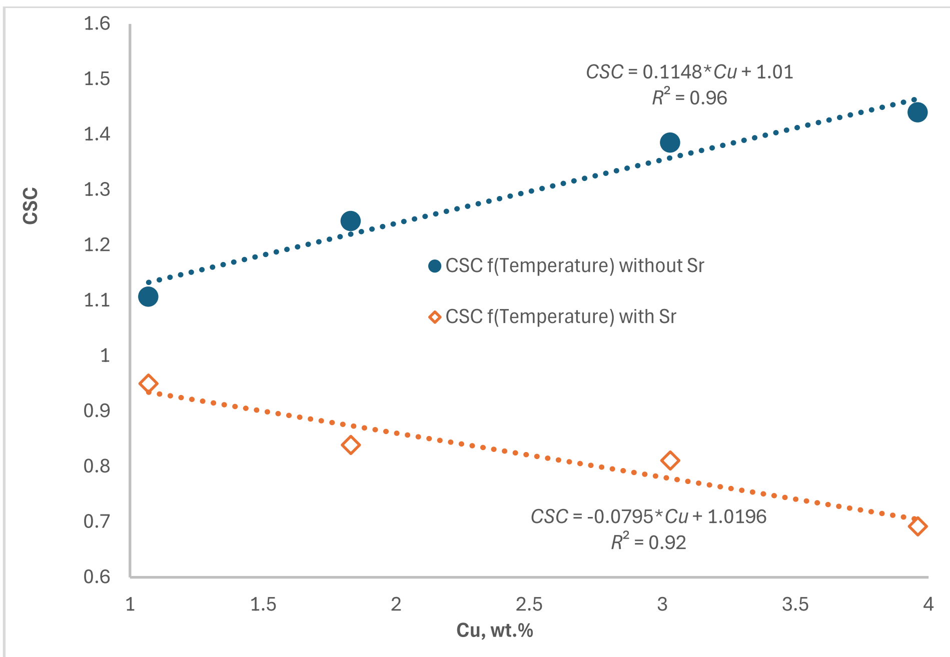

Fig. 5 Impact of Cu and Sr on the CSC expressed by Eq. 5

morphology and enhance the alloy's feeding properties during solidification [32]. Strontium fundamentally transforms the silicon structure from coarse, plate-like formations to finer, fibrous structures. This refinement significantly improves the alloy's ductility by reducing stress concentrations, making it more resistant to cracking during the solidification process. Additionally, Sr influences the solidification mechanics by extending the interdendritic feeding region while reducing the burst feeding region, as documented by Dunkelmann et al. [32]. These changes promote more uniform distribution of silicon and copper-rich phases, which minimizes the formation of brittle networks at grain boundaries and enhances the overall structural integrity of the alloy. The current scientific understanding of silicon phase morphology modification, as reported by Yang et al. [33], focuses on the restricted growth theory [34], which

Table 3 HCI and CSC of evaluated alloys

Alloy	HCI	CSC
AlSi7Mg0.1Cu0.05	0.30	0.587
AlSi7Mg0.3Cu0.05	0.22	0.498
AlSi7Mg0.6Cu0.05	0.01	0.364

includes two principal mechanisms: the impurity-induced twinning mechanism (IIT) [35] and the twin plane re-entrant edge (TPRE) growth mechanism [36]. The IIT mechanism proposes that modifying atoms (Sr and Na) are absorbed at the solid–liquid interface in the silicon growth step, inducing high-density twins. The TPRE mechanism, meanwhile, suggests that silicon growth exhibits strong anisotropy and preferentially occurs at the concave edge along the < 112 > Si growth direction. When modifying atoms accumulate at the re-entrant edge of the twin plane, they hinder silicon growth, forcing changes in both growth direction and morphology. Recent advancements in high-resolution transmission electron microscopy (HRTEM) have revealed that these two mechanisms alone cannot fully explain silicon phase modification in all cases [37]. This suggests that our current understanding of modification mechanisms requires further refinement and supplementation as technology enables more detailed microstructural analysis.

Despite significant advancements in understanding hot tearing phenomena, currently, available models still struggle to accurately predict crack formation across different alloy compositions and casting process parameters. The analytical models developed by Clyne and Davies, Katgerman, and Kamga for predicting hot tearing susceptibility in hypoeutectic aluminum alloys have several fundamental limitations that affect their accuracy. These models primarily rely on theoretical time-based parameters and simplified assumptions about the solidification process without directly incorporating crucial microstructural development stages and material behavior during solidification. The main weakness of these earlier models lies in their oversimplification of the complex solidification phenomena. They often treat the vulnerable period for hot tearing as purely time-dependent without considering the actual physical state of the semi-solid material. For instance, the Clyne–Davies model employs theoretical time intervals during which the alloy is supposedly vulnerable to cracking. Still, it doesn't account for the actual strength development of the dendritic network or the real-time evolution of the microstructure.

The novel analytical model represents a significant advancement because it incorporates actual experimental measurements of critical transformation points during solidification, specifically the DCT and Rigidity temperature. The DCT marks the moment when dendrites first begin to interact and form a coherent network. At the same time, the Rigidity temperature indicates when the material develops significant mechanical strength to resist deformation. By incorporating these experimentally determined parameters from TA, the novel model more accurately reflects the physical reality of the solidification process. Furthermore, TA parameters used in the novel model can capture the effects of different cooling rates, alloy compositions, and processing conditions on the development of the dendritic structure. This makes the model more versatile and applicable to real casting conditions, unlike the earlier models, which often struggled to account for these variables effectively.

The accuracy of the novel method was validated using experimental data from Bozorgi et al., who cast three AlSi7MgCu alloys with varying magnesium content (AlSi7Mg0.1Cu0.05, AlSi7Mg0.3Cu0.05, and AlSi7Mg0.6Cu0.05) in dog bone-shaped molds to evaluate crack susceptibility by applying the HCI experimental method. More details related to the experiments that were conducted can be found in the available literature [38]. Table 3 shows the HCI and resulting CSC determined by applying a novel method described by Eq. (5).

Table 3 compares the HCI and CSC of these alloys. The results demonstrate a strong correlation between experimental and analytical methods, revealing that increasing magnesium content significantly reduces the HCI and slightly lowers the CSC. The novel analytical method provides a more efficient alternative to time-consuming experimental evaluations, offering a qualitative approach to predicting cracking susceptibility in Al–Si alloys. By calculating the CSC using Eq. (5), researchers can quickly assess potential hot cracking risks without the need for extensive laboratory testing. A key advantage of the novel model is its ability to accurately account for the transition period between liquid and solid states. Incorporating both DCT and Rigidity temperatures better represents the critical period when the material is most susceptible to hot tearing, providing a more realistic prediction of crack susceptibility. This is particularly important for hypoeutectic aluminum alloys, where the formation and development of the dendritic network plays a crucial role in determining hot tearing susceptibility. Integrating experimental TA data also enables the novel model to better account for variations in casting conditions and alloy compositions, thereby making it more reliable for practical applications in industrial casting processes. This makes it a more valuable tool for optimizing casting parameters and reducing the incidence of hot tearing in real-world casting operations. However, to further validate its reliability and enhance its predictive capabilities, the novel model needs to be extensively tested under various industrial casting conditions and refined based on the obtained feedback.

4 Conclusions

This research presents a novel analytical model for predicting the crack susceptibility coefficient in cast hypoeutectic aluminum alloys based on critical transformation temperatures during solidification. Our findings reveal that increasing copper content from 1.07 to 3.96 wt.% in AlSi6 alloys significantly raises the CSC from 1.1 to 1.44, confirming industry observations that higher copper levels increase hot tearing susceptibility. Importantly, we discovered that adding strontium (140 ppm) provides a beneficial effect across all copper levels tested, with the most dramatic improvement in the high-copper AlSi6Cu4 alloys, where the CSC decreased from 1.44 to 0.69. The experimental results show that increasing copper content progressively depresses both the dendrite coherency temperature and rigidity temperatures, with copper additions reducing the dendrite coherency temperature from 614.75 to 605.16 °C and the rigidity temperature from 569.18 to 562.23 °C. These temperature shifts correspond with changes in solid fraction development, as the solid fraction at DCT decreased from 20.75 to 12.14% and at the rigidity temperature from 85.02 to 66.14% with increasing copper content. These measurements reveal significant structural changes during solidification that directly influence susceptibility to hot tearing. Our temperature-based CSC model demonstrated strong correlation with experimental Hot Cracking Index measurements when validated against AlSi7MgCu alloys with varying magnesium content. Both metrics showed a consistent decrease with increasing magnesium content, confirming the model's ability to predict hot tearing tendencies accurately.

The novel analytical model's key innovation lies in its utilization of experimentally determined critical transformation temperatures derived from cooling curve analysis. This approach offers significant advantages by considering the actual physical state of the semi-solid material rather than relying on theoretical time intervals. The model effectively captures how varying cooling rates affect dendritic structure development and utilizes temperature as a parameter that remains independent of sample mass, thereby improving the reproducibility and reliability of predictions. The integration of cooling curve analysis data has significantly enhanced our understanding of how alloying elements and modifiers affect critical transformation points, enabling more accurate prediction of hot tearing susceptibility. This methodology leverages thermal analysis techniques that are already widely implemented in aluminum casting facilities, making it practical and accessible for industry applications without requiring new equipment investments. For industrial applications, this model provides foundries with a valuable tool for predicting potential hot tearing locations within castings before production. It enables the optimization of alloy compositions to minimize the risk of hot tearing based on quantitative data, rather than relying on trial and error. The model also allows better control of casting parameters, resulting in higher-quality products and reduced scrap rates. Additionally, it enhances the accuracy of solidification simulations by incorporating experimentally determined parameters that reflect the real-world behavior of aluminum alloys during casting.

Our future work will focus on extensive testing under varied industrial casting conditions to validate the model's reliability further and enhance its predictive capabilities across a broader range of aluminum alloys and process parameters. This continued refinement will transform hot tear prediction from an art to a science, improving both efficiency and quality in aluminum casting operations.

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Declarations

Conflict of interest The authors declare no competing interests.

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