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Effect of Sc on stress-strain and hot tearing susceptibility of Al-Cu intercrystalline liquid film

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Abstract: Al-Cu alloys exhibit promising industrial applications owing to their low density and superior mechanical properties. However, their widespread adoption is severely limited by high hot tearing susceptibility. Hot tearing is closely related to the stress change and fluidity of the intergranular liquid films during the final stage of solidification. Due to the influences of grain size, liquid film thickness, and various defects, conventional polycrystalline samples cannot accurately reflect the stress-strain characteristics of the liquid films. To circumvent these inherent limitations in polycrystalline samples, a custom-designed device was developed to investigate the stress-strain behavior of monocrystalline intergranular liquid films. The effect of Sc on stress-strain of liquid films at the end of Al-Cu solidification was investigated using the self-made device. Meanwhile, combining the T-shaped mold experiment and differential thermal analysis, the relationship between the stress-strain of the liquid films and hot tearing susceptibility was analyzed. The temperature and stress fields during solidification were simulated using ProCAST. The results indicate that the addition of Sc refines the dendrites, modifies the morphology of θ-Al_2Cu, alleviates the stress concentration during the solidification process, and prolongs the liquid feeding duration, thereby reducing the hot tearing susceptibility of the alloys. Numerical simulation results of temperature field, stress field, and hot tearing indicator of T-shaped mold are in good agreement with the experimental observations.

Keywords: Al-Cu alloys; hot tearing susceptibility; rare earth element; liquid films; stress-strain characteristics

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1 Introduction

Al-Cu alloys exhibit excellent strength at both room and high temperatures, low density, and good machinability, making them widely used in industries such as construction, automotive, marine, and aerospace[1, 2]. Especially for Al-Cu alloys with a Cu content ranging from 4.5wt.% to 5.3wt.%, aging treatment can elevate their tensile strength to levels comparable to that of steels, making them indispensable in industrial lightweighting process. However, due to the wide solidification temperature range and well-developed dendrites, the Al-Cu alloys exhibit a large shrinkage force during solidification, resulting in a high susceptibility to hot tearing[3, 4]. Hot tearing, a prevalent defect in alloy casting processes, critically compromises the quality and service life of castings. During the final stage of solidification, extensive precipitation of the solid phase occurs while the residual liquid phase persists as thin liquid films within the interdendritic spaces of the solid skeleton. These liquid films would be ruptured under contraction-induced stresses, resulting in intergranular separation. Hot tearing will not manifest if such intergranular separation is effectively healed through liquid feeding mechanisms. Conversely, insufficient feeding allows these separations to act as crack initiation sites, ultimately propagating into macroscopic hot cracks[5-8]. At present, the hot tearing of Al-Cu alloys has been extensively and deeply studied[9-13]. Sabau et al.[14] studied the hot susceptibility of multicomponent, non-grain-refined Al-Cu alloys during permanent mold casting. The results show that the multicomponent Al-Cu alloys with a Cu content above 7wt.% exhibit good hot tearing resistance compared to those commercial Al-5Cu

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alloys. The study by Han et al.[15] on the relationship between low-melting-point (LMP) eutectic content and hot tearing susceptibility in ternary Al-Cu-Mg alloys during solidification revealed that the Al-4.6Cu-0.4Mg alloy which contained the smallest fraction of LMP eutectics was most prone to hot tearing. Ganjehfard et al.[16] investigated the hot tearing susceptibility of Al-Cu alloys containing excess Fe and Si, and found that the β-CuFe platelets disrupted the tear healing by blocking interdendritic feeding channels, while the α-Fe intermetallics improved the hot tearing resistivity due to their compact morphology and high melting point. Rajagukguk et al.[17] experimentally evaluated hot tearing behavior in Al-Cu alloys with varying Cu content using both horizontal and vertical constrained rod casting (CRC) molds, demonstrating that the horizontal CRC mold more clearly revealed the effect of rod length and Cu composition on the average hot tearing susceptibility. The application of rare earth as grain refiners to enhance the hot tearing resistance has been well documented in studies[18-21]. Zhang et al.[22] investigated the effect of yttrium (Y) on the hot tearing susceptibility of Y_3O_2/Al_5Cu composites, finding that Y addition reduced solidification temperature range and generated Al_8Cu_4Y phases. These phases, synergistically with Al_2Cu phases, facilitated intergranular bridging that inhibited crack initiation and propagation. However, the effect of scandium (Sc) on hot tearing susceptibility of Al-5Cu alloys has not been reported yet.

In recent years, semi-solid tensile testing has made significant contributions to understanding hot tearing mechanisms[23]. Zhao et al.[24] investigated the relationship between semi-solid deformation and hot tearing susceptibility of binary Mg-Ca alloys by semi-solid tensile experiments, and the results indicated that Mg-0.5Ca alloy exhibited the highest hot tearing susceptibility due to its extremely low ductility even at a high solid fraction of 0.96 and the highest linear contraction. Subroto et al.[25] studied the tensile mechanical properties of an as-cast AA7050 alloy in a near-solidus temperature regime, and revealed that the strength decreases with increasing temperature and decreasing strain rate, while the ductility decreases with the increase of temperature and strain rate. Existing studies on hot tearing predominantly focused on macroscopic perspectives, and are unable to accurately reflect the rheological behavior of intergranular liquid films at the single-grain level. This study employs a self-developed device for characterizing stress-strain behavior of intergranular liquid films to investigate the effect of Sc on hot tearing susceptibility in Al-5Cu alloys. Combining T-shaped mold experiment, differential thermal analysis, and numerical simulations, the relationship between the rheological behavior of liquid films and hot tearing susceptibility was studied. The findings provide theoretical guidelines for developing Al-Cu alloys with enhanced hot tearing resistance.

2 Materials and experiment

The experimental raw materials comprised pure Al (99.99wt.%), Al-50Cu intermediate alloy and Al-2Sc intermediate alloy. Pure Al was placed in a crucible with the inner wall coated with boron nitride, and was melted at 700 °C in a resistance furnace. Al-50Cu and Al-2Sc were added after holding for 30 min. Then, the temperature continued to rise to 760 °C and held for another 30 min. During this period, the melt was stirred three times and refined with hexachloroethane. The temperature continued to rise to 800 °C and held for 40 min. Finally the melt was poured into the mold preheated to 200 °C. The chemical compositions of the alloys used in the experiment are shown in Table 1.

Table 1: Chemical compositions of Al-5Cu-*x*Sc alloys (wt.%)

Alloy	Cu	Sc	Al
Al-5Cu	4.965	–	Bal.
Al-5Cu-0.01Sc	4.987	0.012	Bal.
Al-5Cu-0.02Sc	5.087	0.021	Bal.
Al-5Cu-0.03Sc	5.023	0.029	Bal.

Figures 1(a) and (b) schematically illustrates the custom experimental setup for characterizing stress-strain behavior of monocrystalline intergranular liquid films. To simulate the unit structure of "(α-Al)-liquid film-(α-Al)" during terminal solidification of Al-Cu alloys, a configuration was designed using two monocrystalline silicon wafers sandwiching an alloy liquid film. The furnace temperature was raised to 680 °C and held for 40 min to achieve complete alloy melting and interfacial bonding with silicon wafers. The uniaxial tension was applied at a strain rate of 2 mm·min^{-1} after the furnace temperature was cooled to the test temperature and held for 30 s.

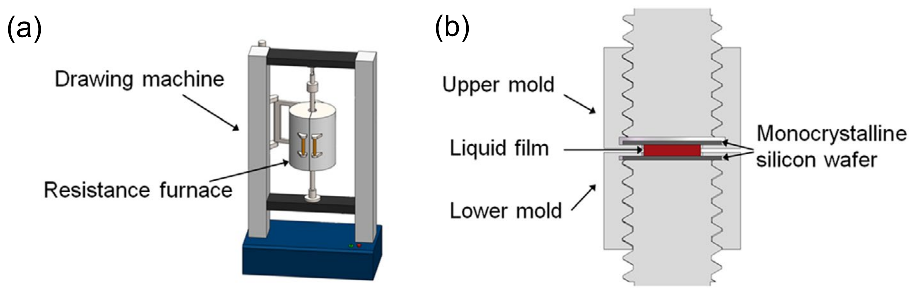

Fig. 1: Schematic diagram of experimental setup for characterizing stress-strain behavior of monocrystalline intergranular liquid films (a), fixture and specimen configuration (b)

The T-shaped mold enhanced the constraint of the mold on alloys during the solidification and shrinkage process. As shown in Fig. 2(a), the T-shaped mold hot tearing experiment setup consisted of a T-shaped casting mold and a data acquisition system. A thermocouple was inserted through a small hole at the left end to collect temperature changes at the hot spot during the solidification process. In order to collect the load changes, a force sensor was fixed to the base and connected to the casting through a rod. The schematic diagram of the differential thermal analysis experimental setup is shown in Fig. 2(b). Two 10 mm thick thermal baffles were placed at the top and bottom of the crucible to ensure the heat is transferred as radially as possible. Due to the difference in thermal conductivity between the solid and liquid, the temperature difference between the center and the edge of the alloy would progressively increase during solidification. When the dendrites begin to impinge and form a continuous framework, heat can be conducted more efficiently along the solid network in the radial direction, causing the temperature difference between the center and the edge to decrease. When the temperature difference reaches its maximum, it indicates that the dendrites start to contact with each other, and the central temperature at this time is defined as the dendrite coherence temperature, denoted as T_{coh}.

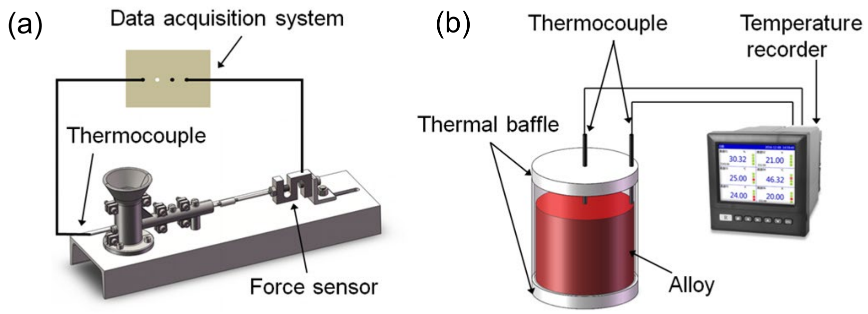

Fig. 2: Schematic diagram of experimental setup: (a) T-shaped mold experiment; (b) differential thermal experiment

The prediction of hot tearing susceptibility of Al-5Cu-*x*Sc alloys was based on the cracking sensitivity coefficient (CSC) model established by Clyne and Davies[8]. Several studies[4, 9, 18, 26] have demonstrated the accuracy of CSC model in predicting hot tearing susceptibility of aluminum alloys. The duration spanning from solid fraction (f_S) 0.4 to 0.9 during the solidification is defined as the stress relaxation time, denoted as t_R. During this stage, a sufficient liquid phase enables effective relexation of contraction stresses and adequate feeding of intergranular gaps, thereby making hot tearing hardly occur. The vulnerable time, denoted as t_V, is defined as the duration spanning from a solid fraction (f_S) of 0.9 to 0.99 during solidification. During this stage, the increasing solid separates the rest liquid into independent molten pools, making it difficult to feed and prone to hot tearing. The value of CSC is the ratio of t_V to t_R, and its calculation formula is as follows:

$$\mathrm{CSC}=\frac{t_V}{t_R}=\frac{t_{0.99}-t_{0.9}}{t_{0.9}-t_{0.4}} \tag{1}$$

where $t_{0.4}$, $t_{0.9}$, and $t_{0.99}$ represent the moments when f_S is 0.4, 0.9, and 0.99, respectively.

The solid phase fraction of the alloy is calculated by the Newton's baseline method, and its formula is as follows[27]:

$$f_S=\frac{\int_{t_L}^{t}\left[\left(\frac{dT}{dt}\right)_{cc}-\left(\frac{dT}{dt}\right)_{bl}\right]dt}{\int_{t_L}^{t_S}\left[\left(\frac{dT}{dt}\right)_{cc}-\left(\frac{dT}{dt}\right)_{bl}\right]dt} \tag{2}$$

where cc represents the cooling curve, bl represents the baseline, $\left(\frac{dT}{dt}\right)_{cc}$ represents the first derivative of the cooling curve, $\left(\frac{dT}{dt}\right)_{bl}$ represents the first derivative of the baseline, and t_L, t_S are the start and end moments of solidification.

The temperature field and stress field during the solidification process of Al-5Cu-*x*Sc alloy in the T-shaped mold experiment were simulated using ProCAST software. The casting parameters are as follows: the direction of gravity is set to be vertically downward; the materials for the alloy, mold, and graphite ring are specified as the experimental Al-Cu alloy, HT250 gray cast iron, and graphite, respectively; the interfacial heat transfer coefficients are assigned as 2,000 $W\cdot m^{-2}\cdot K^{-1}$ between the metal mold and the alloy, and 500 $W\cdot m^{-2}\cdot K^{-1}$ at both the mold-graphite ring and alloy-graphite ring interfaces; the pouring conditions are set with a pouring temperature of 750 °C, a mold preheating temperature of 200 °C, a pouring duration of 5 s, and air cooling as the solidification condition.

3 Results and discussion

3.1 Stress-strain characteristics of liquid film between two single grains

The liquid film theory postulates that during the final stage of solidification, decreasing temperature reduces the amount of liquid phase, leading to progressive thinning of intergranular films. Strain becomes concentrated at residual hot spots, and when the accumulated strain exceeds a critical threshold, the film ruptures, thereby initiating hot tearing. According to solidification shrinkage compensation theory, the tearing propagation can be impeded if surrounding residual liquid effectively feeds the ruptured film. Therefore, at the end of solidification, the stress-strain characteristics of the near-eutectic liquid film (sandwiched between α-Al dendrites) are crucial to the occurrence of hot tearing. Guided by phase diagram and computational results from Bo et al.[28], high-temperature tensile testing was conducted on eutectic Al-33.3Cu and Al-33.3Cu-0.04Sc liquid films between two monocrystal wafers, and the result is shown in Fig. 3.

Figure 4 reveals analogous evolutionary patterns in the stress-displacement curves of both alloy liquid films. The tensile process exhibits three distinct stages. Elastic response stage: linear correlation between stress and displacement

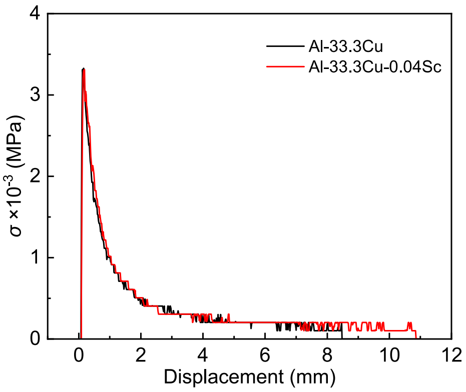

Fig. 3: Stress-displacement curves of alloy's liquid films

during initial loading according to Fig. 3. Plastic instability stage: after the stress reaches the limit value, the liquid film necking occurs [Fig. 4(b)], the load required to continue deforming the liquid film decreases, and the stress begins to decline. Ductile rupture stage: the liquid film does not rupture immediately but undergoes progressive necking as the internal liquid flows, maintaining a low-stress state [Fig. 4(c)] until eventual fracture.

It can be seen from Fig. 3 that the stress limit values of the Al-33.3Cu and Al-33.3Cu-0.04Sc liquid films are almost the same, indicating that their abilities to resist hot tearing nucleation are comparable. The difference is that the liquid film of Al-33.3Cu-0.04Sc alloy has a longer fracture displacement and thus a longer fracture time. The fracture displacement of the Al-33.3Cu-0.04Sc liquid film was 10.86 mm, significantly longer than that of the Al-33.3Cu liquid film (8.45 mm). During final stage of solidification, the residual liquid films would deform along with the mutual separation of dendrites when subjected to solidification shrinkage. Due to the longer fracture displacement of the liquid film containing Sc, a longer time could be provided for the liquid feeding, thereby reducing the hot tearing susceptibility of the alloy.

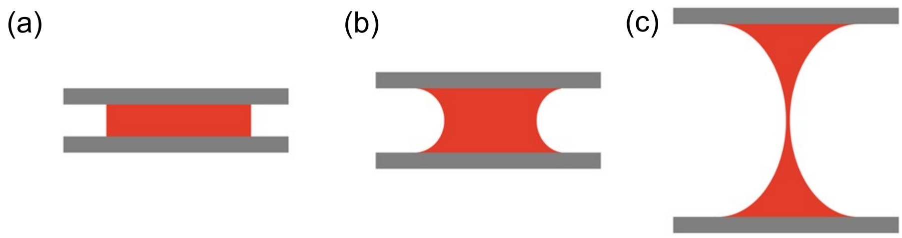

Fig. 4: Schematic diagram of morphological changes during stretching of liquid films (a–c)

3.2 T-shaped mold hot tearing experiment

The result of the T-shaped hot tearing experiment for Al-5Cu-*x*Sc alloys is shown in Fig. 5. During the solidification, constrained shrinkage generates internal stress. When hot tearing occurs, the stress at the hot spot would be released instantly. Hot tearing initiation is identified by abrupt load drops or reduced load rate (indicated by sudden decreases in the first derivative of load-time curves), with the corresponding temperature defined as the beginning temperature of hot tearing (T_b). The lower the T_b, the higher the corresponding f_S, which effectively counteracts the stress induced by solidification shrinkage and reduces hot tearing susceptibility. As shown in Fig. 5(a), Al-5Cu alloy exhibits the highest T_b, and the load curve shows an obvious decrease, which means that a relatively severe hot tearing occurs, indicating that it has a high sensitivity to hot tearing. With the increase of Sc content, the T_b progressively decreases, and the hot tearing susceptibility decreases. Especially for Al-5Cu-0.03Sc, there is no obvious drop in the load curve. The macroscopic cracks of the specimens are shown in Fig. 6. The hot tearing in the Al-5Cu alloy is the most severe, propagating along the entire length of the rod. However, with increasing Sc content, the cracks progressively become narrower and discontinuous.

3.3 Differential thermal analysis and solidification curve analysis

The differential thermal analysis result of Al-5Cu-*x*Sc alloys is shown in Fig. 7. According to the binary Al-Cu phase diagram, Al-5Cu exhibits a broad solidification temperature range with dendritic growth characteristics. This leads to premature contact of dendrites which makes the alloy exhibit a high T_{coh}, as shown in Fig. 7(a). A high T_{coh} means early formation of the solid skeleton, which shortens the effective liquid feeding duration and prolongs the feeding-free stage, as the remaining liquid is divided into isolated molten pools. Meanwhile, the earlier the solid phases come into contact, the greater the stress accumulation during solidification shrinkage, leading to increased hot tearing susceptibility. With the increase of Sc content, the T_{coh} decreases, as shown in Fig. 7. The later the dendritic framework forms, the longer the liquid phase can sustain feeding, thereby significantly reducing the hot tearing tendency of the alloys.

The solidification curve analysis of Al-5Cu-*x*Sc alloys is shown in Fig. 8. The black curves represent the variation of temperature with time during the cooling process, the red curves are the first-order derivatives of the cooling curves, and the green curves represent the baselines. The

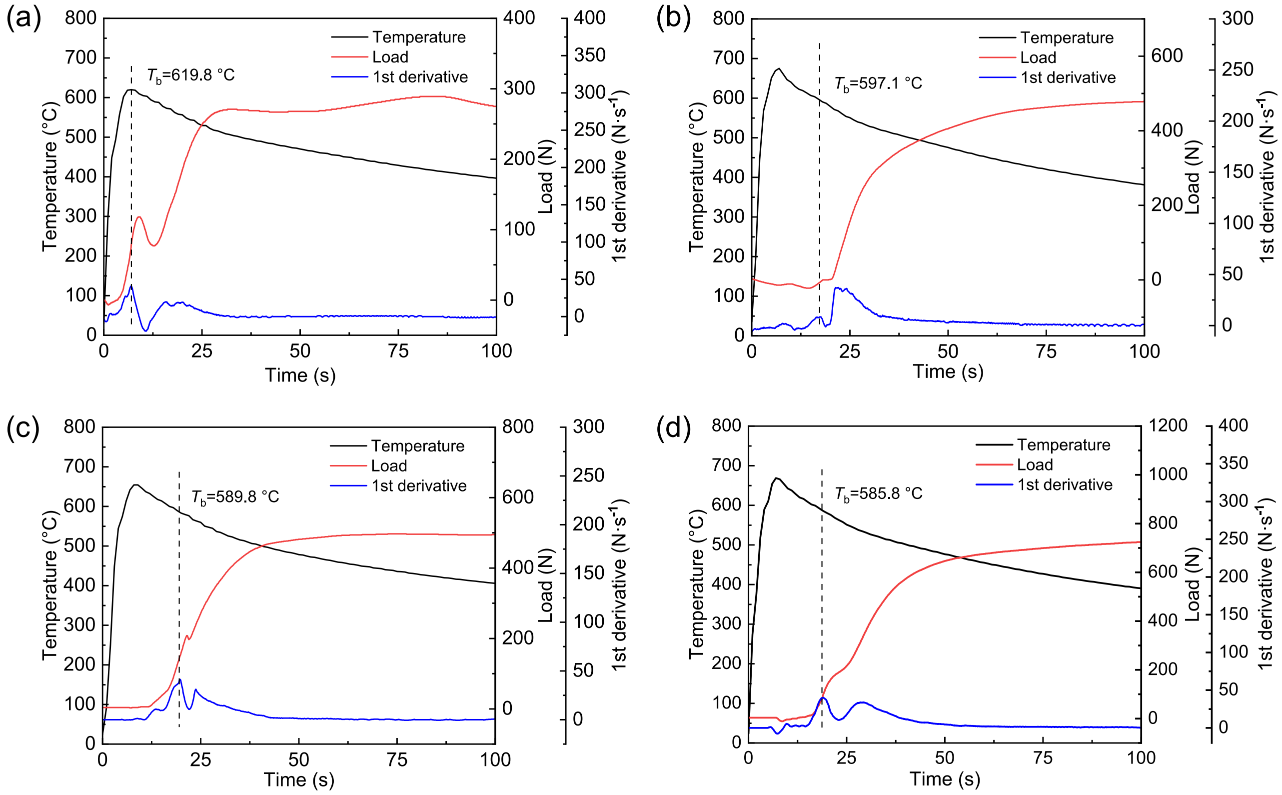

Fig. 5: Load and temperature curves of T-shaped mold experiment for Al-5Cu-*x*Sc alloys: (a) *x*=0; (b) *x*=0.01; (c) *x*=0.02; (d) *x*=0.03

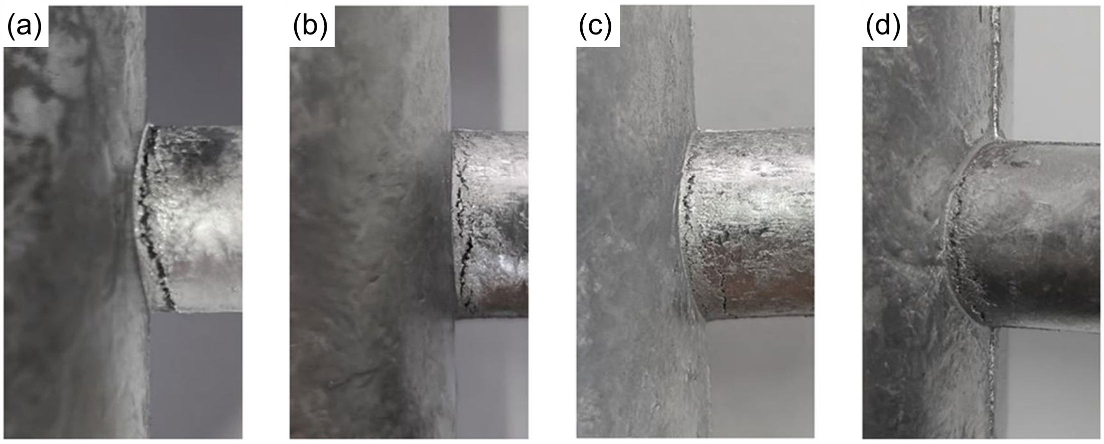

Fig. 6: Macroscopic cracks of Al-5Cu-*x*Sc alloys: (a) *x*=0; (b) *x*=0.01; (c) *x*=0.02; (d) *x*=0.03

baseline represents the solidification process without phase transformations. During the solidification, when the solid phase precipitates or the phase transformation occurs, the heat is released, and the cooling rate decreases, thereby an exothermic peak appears on the first derivative of the cooling curve. The precipitation temperatures of each phase in the alloys can be obtained from Fig. 8, as shown in Table 2. With the progress of solidification, α-Al first precipitates in the alloy at approximately 653 °C. The dendrites keep growing and come into contact with each other to form the framework. Due to the redistribution of solutes, the liquid phase composition changes accordingly. Finally, the residual liquid films between dendrites approach the eutectic composition, and the eutectic reaction occurs at around 551 °C, generating (α-Al+θ-Al_2Cu) eutectics. It can be seen from the first derivative curves of the cooling curves that there is no obvious precipitation peak of the Sc-containing phase. Due to the extremely small amount of Sc addition, the precipitation peak of the Sc-containing phase in Fig. 8 is not obvious. Therefore, the influence of trace Sc on the solidification temperature range of the alloy is very small. The liquidus temperatures of the alloys are approximately 653 °C, with a difference of only about 2.6 °C, while the solidus temperatures are around 542 °C, differing by approximately 2.9 °C.

The CSC calculated via Eqs. (1) and (2) is presented in Fig. 9. A progressive reduction in CSC is observed with increasing Sc content, indicating enhanced the resistance to hot tearing due to prolonged liquid feeding duration and reduced vulnerable period. This trend aligns with experimental findings from T-shaped mold hot tearing experiment.

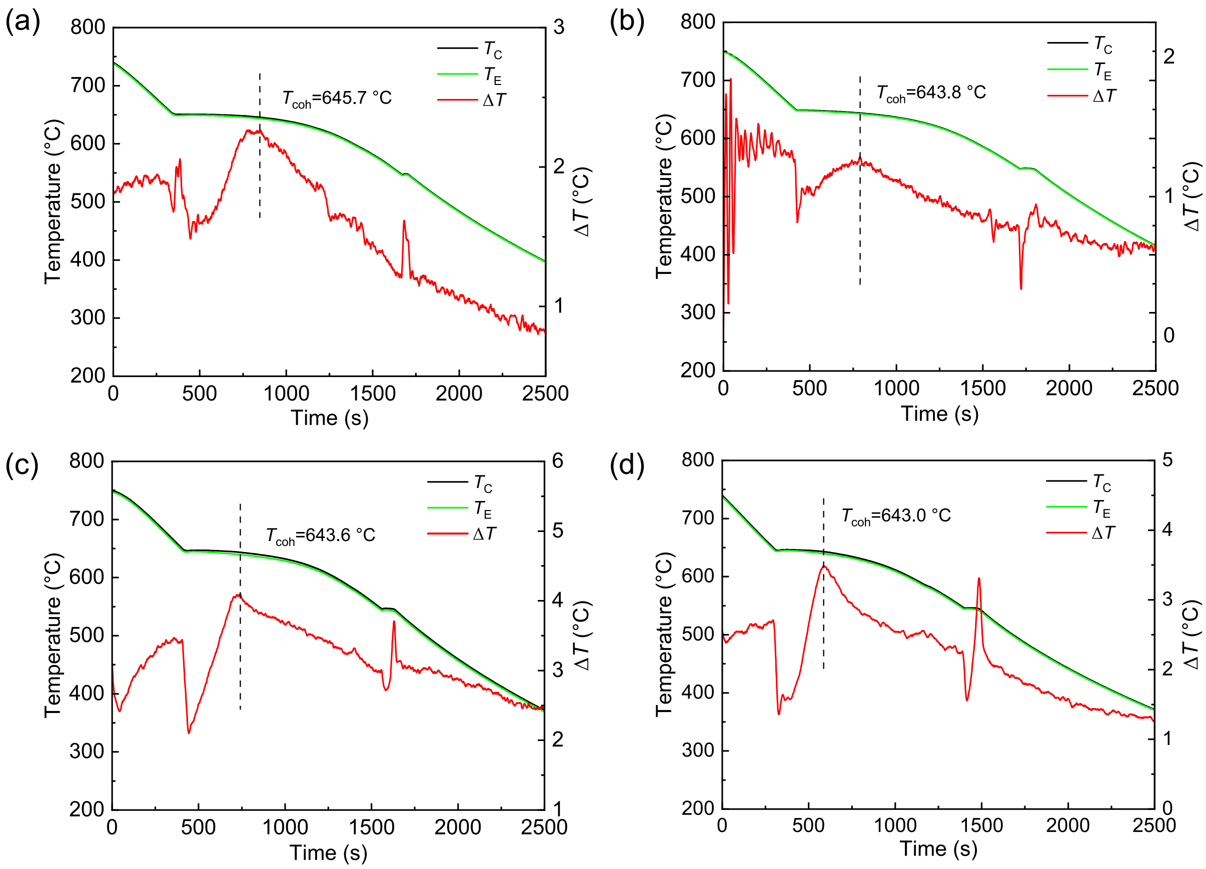

Fig. 7: Differential thermal analysis and T_{coh} of Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03 (where T_c denotes the temperature in the core and T_E in the edge of the melt)

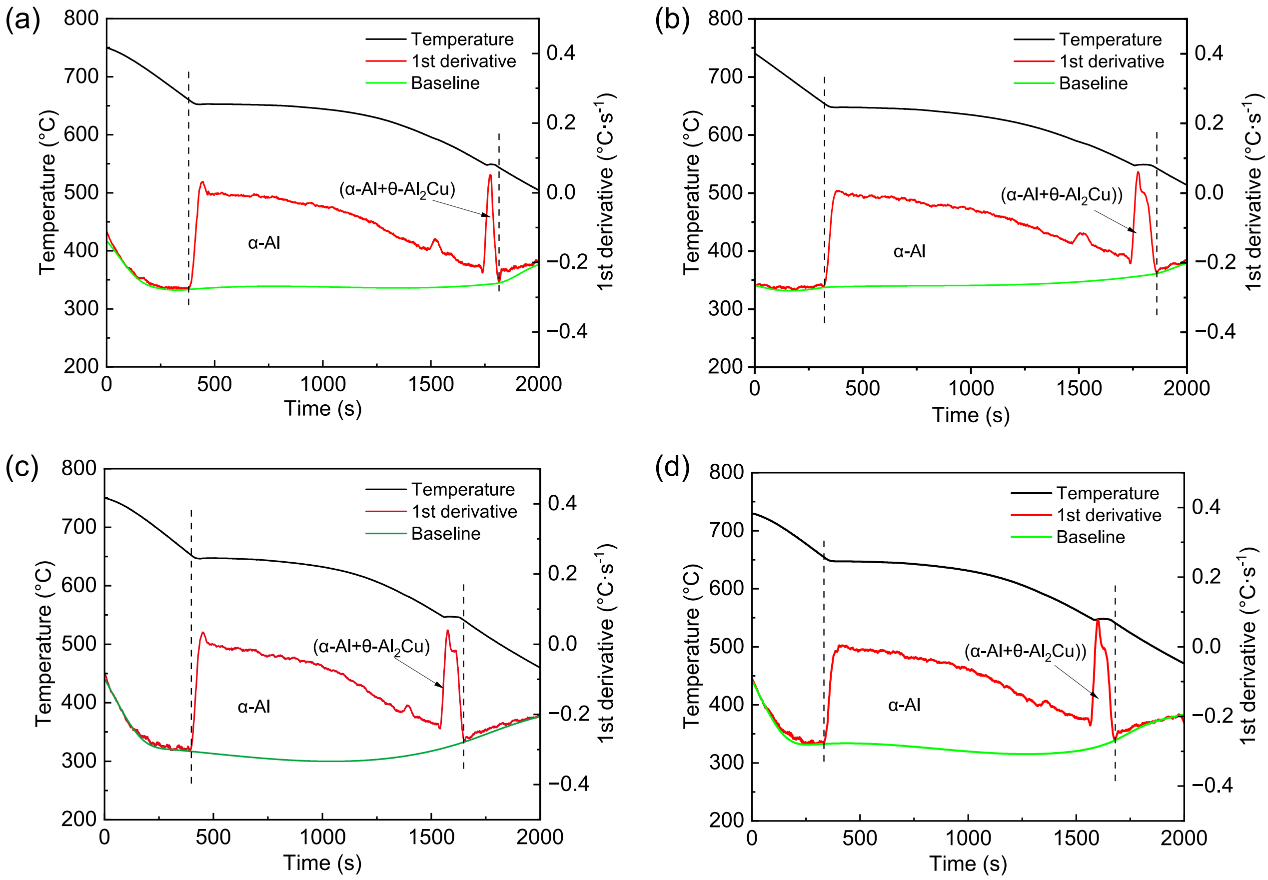

Fig. 8: Cooling curves, first derivative curves and baselines of Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03

Table 2: Phase precipitation temperatures of Al-5Cu-*x*Sc alloys

Alloy	Precipitation temperature (°C)	
	α-Al	(α-Al+θ-Al_2Cu)
Al-5Cu	654.7	551.4
Al-5Cu-0.01Sc	653.9	550.5
Al-5Cu-0.02Sc	652.1	550.8
Al-5Cu-0.03Sc	654.5	550.2

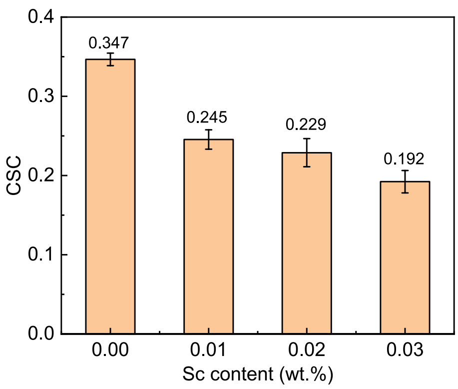

Fig. 9: CSC of Al-5Cu alloys with different Sc contents

3.4 Numerical simulation analysis of temperature and stress fields during solidification

The numerical simulation results of the temperature and stress fields during the solidification of the castings in the T-shaped mold hot tearing experiment are shown in Figs. 10 and 11. The main body of the casting cools slowly due to the large wall thickness, while the thin crossbar cools quickly. A hot spot exists at the connection between the two, where the temperature gradient is very large. This geometry-induced cooling unevenness generates concentrated contraction stresses, creating preferential conditions for hot tearing initiation. The simulated stress field during solidification strongly supports this conclusion. As shown in Fig. 11, the stress is concentrated at the hot spot of the casting. With increasing Sc content, the stress concentration degree at the hot spot progressively decreases, and the hot tearing indicator (HTI) decreases from 0.0157 to 0.0115. This reduction in HTI indicates a lowered hot tearing susceptibility of the alloys, which aligns consistently with experimental observations.

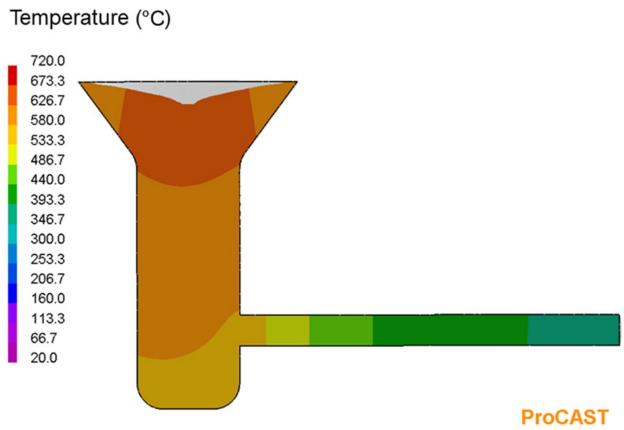

Fig. 10: Numerical simulation of temperature field during the solidification of Al-5Cu-0.03Sc alloy

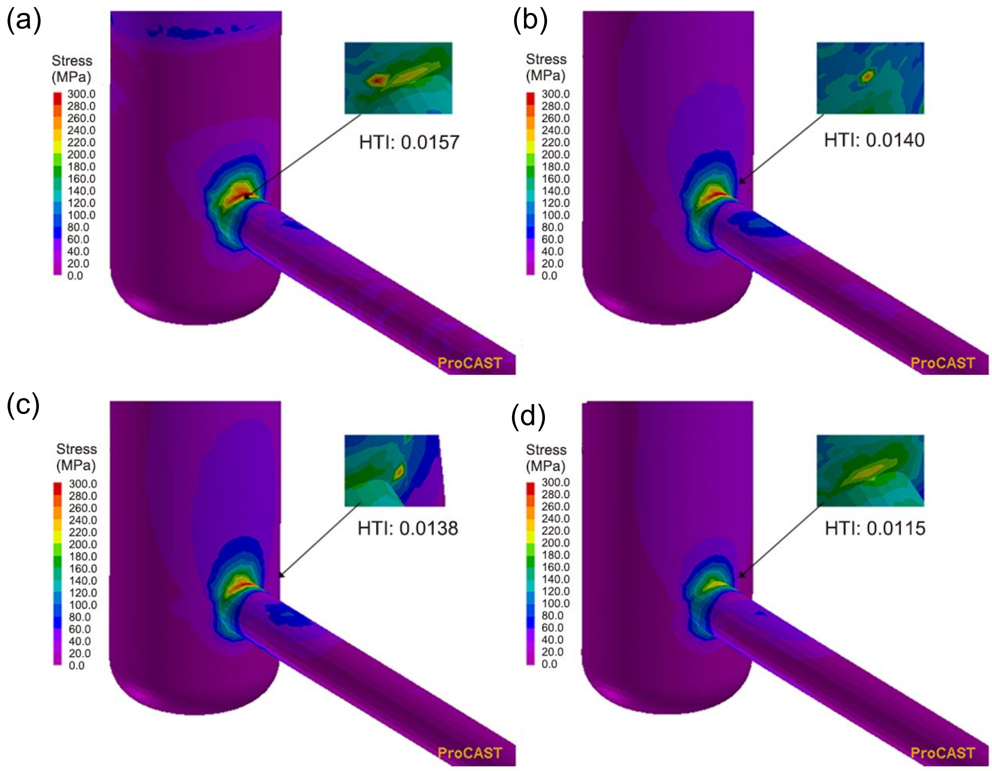

Fig. 11: Numerical simulation of stress field and HTI of Al-5Cu-*x*Sc alloys: (a) *x*=0; (b) *x*=0.01; (c) *x*=0.02; (d) *x*=0.03

3.5 Microstructure analysis

The XRD test results of Al-Cu alloys with different Sc contents are shown in Fig. 12. The Al-5Cu alloys with a trace amount of Sc added are still mainly composed of α-Al and θ-Al_2Cu. When the Sc content is 0.03wt.%, a small amount of Al_3Sc is detected in the sample, while its diffraction peak is not obvious when the Sc content is low.

The SEM images of the alloy are shown in Fig. 13. The α-Al phase appears as dark-gray dendrites, while the light-gray (α-Al + θ-Al_2Cu) eutectic structure is distributed interdendritically. According to the equilibrium Al-Cu phase diagram, the minimum Cu content for eutectic reaction is 5.7wt.%. However, under non-equilibrium solidification conditions in the T-shaped mold experiment, the eutectic point shifts to lower Cu concentrations, enabling eutectic formation in the air-cooled Al-5Cu alloy. As shown in Fig. 13(a), there are relatively coarse dendrites in Al-5Cu, and the θ-Al_2Cu between the dendrites are mostly continuous long strips. It can be seen from Figs. 13(b–d) that the α-Al dendrites in the Sc-containing alloys are relatively fine, with a higher density of fine, circular or short rod-shaped θ-Al_2Cu particles distributed within the interdendritic regions. The addition of Sc refines the primary α-Al dendrites, resulting in shorter and more numerous feeding channels during terminal solidification, thereby promoting liquid feeding. Furthermore, it also changes the morphology of θ-Al_2Cu. The liquid film containing fine circular θ-Al_2Cu is easier to flow, improving the feeding conditions during terminal solidification. In addition, hot tearing is prone to nucleation and expansion at the tips of the long strip-shaped θ-Al_2Cu, and the circular θ-Al_2Cu is less likely to accumulate stress during solidification and tear the matrix, thereby reducing the hot tearing susceptibility of the alloys.

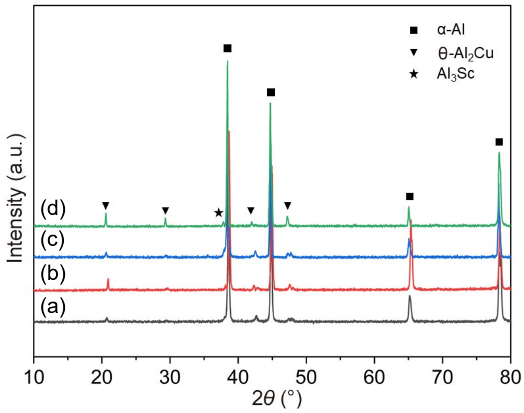

Fig. 12: XRD results of Al-5Cu-*x*Sc alloys: (a) *x*=0; (b) *x*=0.01; (c) *x*=0.02; (d) *x*=0.03

Firstly, the addition of Sc causes the precipitation of Al_3Sc particles during the solidification process. Due to the similarity in structure and size between the Al_3Sc phase and the aluminum matrix, the precipitation of Al_3Sc results in the formation of high-density, stable, spherical particles that are coherently aligned with the matrix. These particles can serve as potential nucleation sites for α-Al, thereby refining the dendrites[29]. Finer grains result in a higher density of grain boundaries per unit volume. The tensile stress induced by solidification shrinkage is accommodated by numerous grain boundaries. This distribution alleviates stress concentration at any individual grain boundary, thereby preventing local stresses from reaching the fracture strength of the intergranular

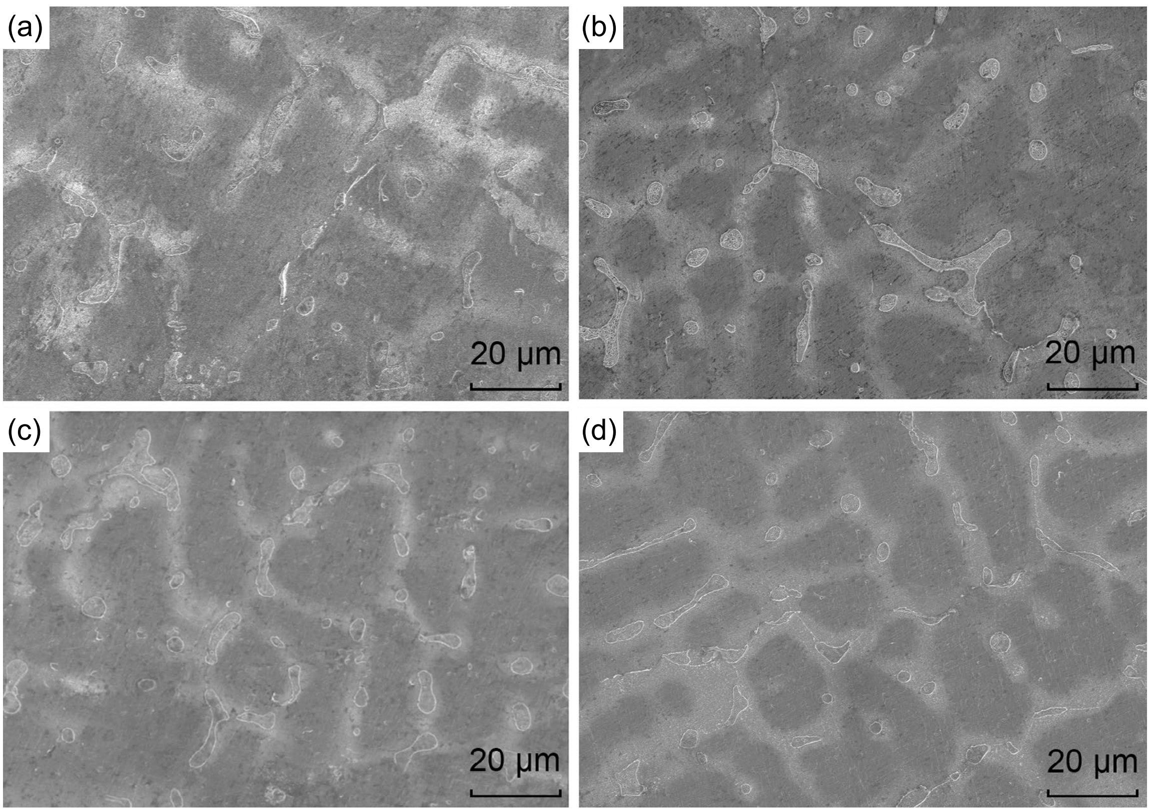

Fig. 13: SEM images of Al-5Cu-*x*Sc alloys: (a) *x*=0; (b) *x*=0.01; (c) *x*=0.02; (d) *x*=0.03

liquid film. In addition, fine-grained structures cause the liquid film to disperse into multiple small liquid films. This distribution provides numerous short feeding channels, and significantly improves liquid feeding. Secondly, for a single liquid film, the addition of Sc increases the fracture displacement, providing a longer period for liquid feeding. Thirdly, the addition of Sc transforms the morphology of the inter-dendritic Al_2Cu into fine spherical or short rod-like structures, promoting the flow of the liquid film in the later stages of solidification. The formation of hot tearing is closely related to the feeding capacity of the liquid film. If the surrounding liquid film can feed the rupture in time, the rupture will be healed and the hot tearing will be suppressed. Thus, the addition of Sc reduces hot tearing susceptibility of the alloy.

4 Conclusions

The self-developed device for characterizing the stress-strain behavior of the intergranular liquid film between two monocrystals was employed to investigate the effect of Sc on the stress-strain of the intergranular liquid film during the final stage of solidification of Al-5Cu alloys. Combining with T-shaped mold hot tearing experiment, differential thermal analysis, and numerical simulation, the effect of Sc on the hot tearing susceptibility of Al-5Cu alloys was investigated. The main conclusions are as follows:

(1) The Sc-containing Al-5Cu alloy liquid film exhibits a stress limit value comparable to their Sc-free counterparts during tensile loading. However, the fracture displacement of Sc-containing liquid film is significantly greater, creating a prolonged time window for liquid feeding to heal the intergranular separation. This enhanced healing capability reduces the hot tearing susceptibility of the alloys.

(2) With increasing Sc content, the hot tearing beginning temperature of the alloys decreases from 619.8 °C to 585.8 °C, accompanied by flatter load curves during solidification. The dendrite coherence temperature decreases from 645.7 °C to 643 °C, and the CSC decreases from 0.347 to 0.192, effectively reducing the duration of the vulnerable, difficult-to-feed solidification interval. These coordinated changes significantly reduce the hot tearing susceptibility, as validated by strong consistency between numerical simulations and experimental results.

(3) The addition of Sc refines the dendritic structures, shortens the interdendritic feeding channels, and modifies the morphology of θ-Al_2Cu phases. These microstructural optimizations promote the liquid feeding and mitigate the stress concentration during solidification, thereby significantly reducing the hot tearing susceptibility of the alloys.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Kim Y, Buchheit R G. A characterization of the inhibiting effect of Cu on metastable pitting in dilute Al-Cu solid solution alloys. Electrochimica Acta, 2007, 52(7): 2437–2446. http://doi.org/10.1016/j.electacta.2006.08.054.

[2] Fan S, Guo X, Li Z, et al. A review of high-strength aluminum-copper alloys fabricated by wire arc additive manufacturing: Microstructure, properties, defects, and post-processing. Journal of Materials Engineering and Performance, 2023, 32(19): 8517–8540. http://doi.org/10.1007/s11665-023-08233-5.

[3] Gawronska E. Different techniques of determination of the cracking criterion for solidification in casting. Procedia Engineering, 2017, 177: 86–91. http://doi.org/10.1016/j.proeng.2017.02.188.

[4] Su M, Zheng W T, Fu D K, et al. Design and application of a multichannel "cross" hot tearing tendency device: A study on hot tearing tendency of al alloys. China Foundry, 2022, 19(4): 327–334. http://doi.org/10.1007/s41230-022-1184-5.

[5] Li Y, Li H, Katgerman L, et al. Recent advances in hot tearing during casting of aluminium alloys. Progress in Materials Science, 2021, 117: 100741. http://doi.org/10.1016/j.pmatsci.2020.100741.

[6] Eskin D G, Suyitno, and Katgerman L. Mechanical properties in the semi-solid state and hot tearing of aluminium alloys. Progress in Materials Science, 2004, 49(5): 629–711. http://doi.org/10.1016/s0079-6425(03)00037-9.

[7] Song J, Pan F, Jiang B, et al. A review on hot tearing of magnesium alloys. Journal of Magnesium and Alloys, 2016, 4(3): 151–172. http://doi.org/10.1016/j.jma.2016.08.003.

[8] Li S, Apelian D. Hot tearing of aluminum alloys a critical literature review. International Journal of Metalcasting, 2011, 11: 23–40. http://doi.org/10.1007/BF03355505.

[9] Yue C, Zheng B, Su M, et al. Effect of Y and Ce micro-alloying on microstructure and hot tearing of as-cast Al-Cu-Mg alloy. Acta Metallurgica Sinica (English Letters), 2024, 37(6): 939–952. http://doi.org/10.1007/s40195-024-01671-7.

[10] Wang Y, Yue C, Su M, et al. Effect of Ce on hot tearing sensitivity of as-cast Al-Cu-Mg-Y alloy. Journal of Materials Engineering and Performance, 2022, 31(8): 6349–6359. http://doi.org/10.1007/s11665-022-06690-y.

[11] Ma C, Rong L, Chen J, et al. Effect of Er and Zr on hot crack resistance and mechanical properties of Al-Cu-Mn-Cd alloy. International Journal of Metalcasting, 2025, 19(3): 1388–1402. http://doi.org/10.1007/s40962-024-01380-y.

[12] Wang Y, Wu S, Xue X, et al. Experimental and numerical study on formation mechanism of linear macro-segregation in low-pressure die casting of Al-Cu-Mn-Ti alloy. Journal of Mechanical Engineering Science, 2015, 231(10): 1946–1955. http://doi.org/10.1177/0954406215623979.

[13] Sabau A S, Milligan B K, Mirmiran S, et al. Grain refinement effect on the hot-tearing resistance of higher-temperature Al-Cu-Mn-Zr alloys. Metals, 2020, 10(4). http://doi.org/10.3390/met10040430.

[14] Sabau A S, Mirmiran S, Glaspie C, et al. Hot-tearing assessment of multicomponent nongrain-refined Al-Cu alloys for permanent mold castings based on load measurements in a constrained mold. Metallurgical and Materials Transactions: B, 2018, 49(3): 1267–1287. http://doi.org/10.1007/s11663-018-1204-0.

[15] Han J, Wang J, Zhang M, et al. Relationship between amounts of low-melting-point eutectics and hot tearing susceptibility of ternary Al-Cu-Mg alloys during solidification. Transactions of Nonferrous Metals Society of China, 2020, 30(9): 2311–2325. http://doi.org/10.1016/s1003-6326(20)65381-x.

[16] Ganjehfard K, Taghiabadi R, Noghani M T, et al. Tensile properties and hot tearing susceptibility of cast Al-Cu alloys containing excess Fe and Si. International Journal of Minerals, Metallurgy and Materials, 2020, 28(4): 718–728. http://doi.org/10.1007/s12613-020-2039-7.

[17] Rajagukguk K, Suyitno S, Saptoadi H, et al. Evaluation of horizontal and vertical constrained rod casting mold on hot tearing susceptibility of Al-Cu alloys. International Journal of Metalcasting, 2024, 18(4): 3329–3341. http://doi.org/10.1007/s40962-023-01250-z.

[18] Tao C, Huang H, Yuan X, et al. Effect of Y element on microstructure and hot tearing sensitivity of as-cast Al-4.4Cu-1.5Mg-0.15Zr alloy. International Journal of Metalcasting, 2021, 16(2): 1010–1019. http://doi.org/10.1007/s40962-021-00666-9.

[19] Gavras S, Easton M A, Gibson M A, et al. Microstructure and property evaluation of high-pressure die-cast Mg-La-rare earth (Nd, Y or Gd) alloys. Journal of Alloys and Compounds, 2014, 597: 21–29. http://doi.org/10.1016/j.jallcom.2014.01.204.

[20] Li M, Wang H, Wei Z, et al. The effect of Y on the hot-tearing resistance of Al-5wt.% Cu based alloy. Materials & Design, 2010, 31(5): 2483–2487. http://doi.org/10.1016/j.matdes.2009.11.044.

[21] Wei Z Q, Zhou Z J, Liu S M, et al. Effects of Y and addition of refiners on hot tearing susceptibility of MgZn-based alloy. International Journal of Metalcasting, 2022, 16: 278–290. http://doi.org/10.1007/s40962-021-00719-z.

[22] Zhang X, Li D, Zeng L, et al. Effect of Y on the hot tearing susceptibility of $3Y_2O_3/Al_5Cu$ composite. Journal of Alloys and Compounds, 2020, 849: 156152. http://doi.org/10.1016/j.jallcom.2020.156152.

[23] Lin Z, Zhao Y, Li T, et al. New insights into the features of hot tearing formation in high-carbon steel under tensile loading. Metallurgical and Materials Transactions: B, 2023, 54(6): 2870–2874. http://doi.org/10.1007/s11663-023-02918-x.

[24] Zhao H, Song J, Wang J, et al. Semi-solid tensile behavior and its relationship with hot tearing susceptibility of Mg-*x*Ca alloys. International Journal of Metalcasting, 2023, 18(2): 1119–1134. http://doi.org/10.1007/s40962-023-01097-4.

[25] Subroto T, Miroux A, Eskin D G, et al. Tensile mechanical properties, constitutive parameters and fracture characteristics of an as-cast AA7050 alloy in the near-solidus temperature regime. Materials Science and Engineering: A, 2017, 679: 28–35. http://doi.org/10.1016/j.msea.2016.10.021.

[26] Pekguleryuz M O, Lin S, Ozbakir E, et al. Hot tear susceptibility of aluminium-silicon binary alloys. International Journal of Cast Metals Research, 2013, 23(5): 310–320. http://doi.org/10.1179/136404610x12738456167267.

[27] Zhou Y, Mao P, Wang Z, et al. Effects of copper content and mold temperature on the hot tearing ssceptibility of Mg-7Zn-*x*Cu-0.6Zr alloys. Metallurgical and Materials Transactions: B, 2018, 49(6): 3444–3455. http://doi.org/10.1007/s11663-018-1389-2.

[28] Bo H, Liu L B, Jin Z P. Thermodynamic analysis of Al-Sc, Cu-Sc and Al-Cu-Sc system. Journal of Alloys and Compounds, 2010, 490(1–2): 318–325. http://doi.org/10.1016/j.jallcom.2009.10.003.

[29] Xu Y, Zhang Z, Gao Z, et al. Effect of Sc on the hot cracking properties of 7xxx aluminum alloy and the microstructure of squeeze castings. Materials (Basel), 2021, 14(22): 6881. http://doi.org/10.3390/ma14226881.