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 the high hot tearing susceptibility. Hot tearing is closely related to the stress change and fluidity of the intergranular liquid films during terminal solidification. Nevertheless, existing hot tearing experiments conducted at the polycrystalline scale fail to accurately capture the stress-strain characteristics of the intergranular liquid films between two monocrystals. In light of this, we developed a custom-designed device for characterizing stress-strain behavior of monocrystalline intergranular liquid films. The effect of Sc on the stress-strain of liquid films at the end of Al-Cu solidification was investigated via the self-made device. Meanwhile, combining the "T" mold experiment and differential thermal analysis, the relationship between the stress-strain of the liquid films and the hot tearing susceptibility was analyzed. The temperature and stress fields during solidification were simulated by 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 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" mold are in agreement with the experimental observations.

Keywords: aluminum-copper alloy; hot tearing susceptibility; rare earth element; liquid films; stress-strain characteristics

1 Introduction

Al-Cu alloys have splendid strength at room and high temperature, low density and good machinability, and are widely used in fields such as construction manufacturing, automotive and marine industries, and aerospace[1, 2]. Especially for Al-Cu alloys with a copper content ranging from 4.5 to 5.3wt.%, after aging treatment, their tensile strength can be on a par with that of steel, and they play an irreplaceable role 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 the solidification process, resulting in these alloys having 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 left 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 nongrain-refined Al-Cu alloys during permanent mold casting. The results show that the multicomponent Al-Cu alloys with a Cu content above 7wt.% have good hot tearing resistance compared with commercial Al-5Cu 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 horizontal and vertical constrained rod casting (CRC) molds, demonstrating that the horizontal CRC mold provided a clearer effect of rod length and Cu composition on the average hot tearing susceptibility value. 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 on the hot tearing susceptibility of Y_3O_2/Al5Cu composites, finding that Y addition reduced solidification temperature range and generated Al8Cu4Y phases. These phases, synergistically with Al_2Cu phases, facilitated intergranular bridging that inhibited crack initiation and propagation. However, the effect of Scandium on the hot tearing susceptibility of Al-5Cu alloys has not been reported yet.

For the past few years, Semi-solid tensile tests have made significant contributions[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 and the ductility decreases with the increase of temperature and strain rate. The existing studies on hot tearing predominantly focused on macroscopic perspectives, and could not accurately reflect the rheological properties 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. And combining T-shaped mold experiment, differential thermal analysis, and numerical simulations, the relationship between the rheological properties of liquid films and hot tearing susceptibility is 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 Aluminum (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 ℃ in a resistance furnace. Al-50Cu and Al-2Sc were added successively after holding for 30 minutes. Then the temperature continued to rise to 760 ℃ and held for 30 minutes. During this period, the melt was stirred three times and refined with hexachloroethane. The temperature continued to rise to 800 ℃ and held for 40 minutes. Finally the melt was poured into the mold preheated to 200 ℃. The chemical composition of the alloys used in the experiment is shown in Table 1.

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

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

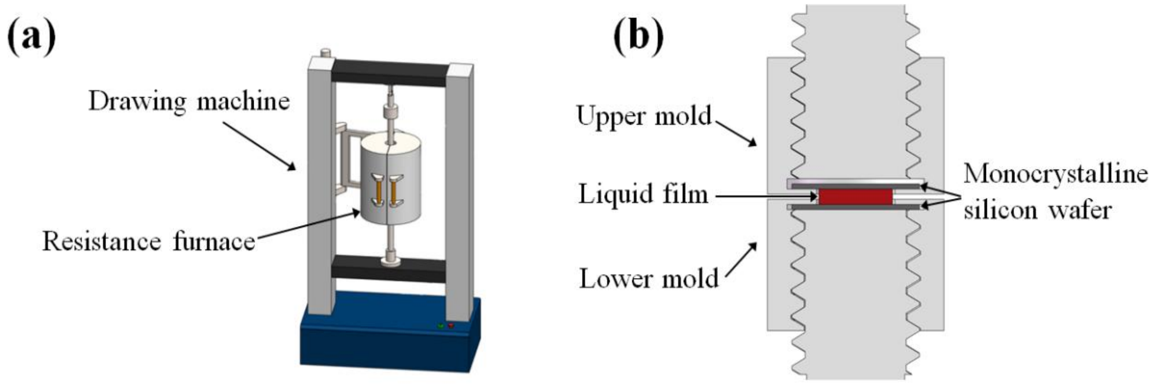

Fig. 1: Schematic diagram of (a) the experimental setup for characterizing stress-strain behavior of monocrystalline intergranular liquid films; (b) the fixture and specimen configuration

Fig. 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. Since the solidus of the Al-5Cu is 548°C, the selected test temperature was 551 °C to replicate the thermal conditions during terminal solidification. Specimens were prepared as 0.7 mm-thick discs (7.9 mm diameter) through precision grinding and polishing.

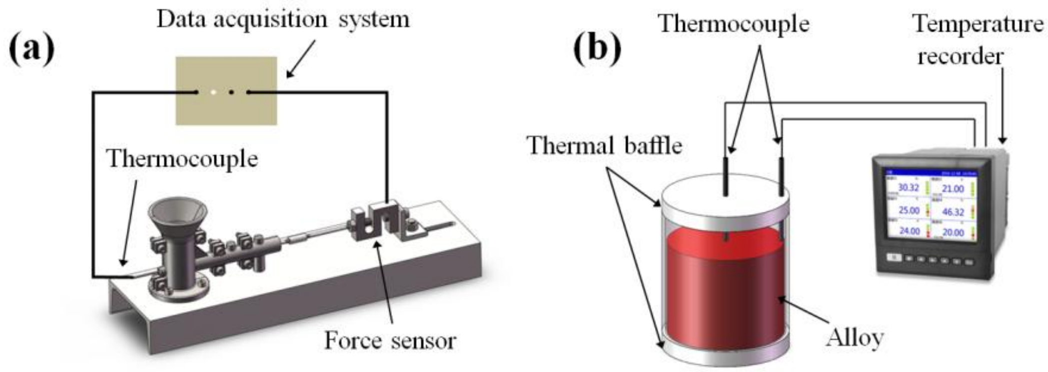

Fig. 2: Schematic diagram of experimental setup: (a) T-shaped mold experiment; (b) differential thermal experiment

The T-shaped mold enhanced the constraint of the mold on the alloys during the solidification and shrinkage process. As shown in Fig. 2 (a), the T-shaped mold hot tearing experiment consisted of a T-shaped casting mold and a data acquisition system. The T-shaped mold was fixed to the cast iron base after being connected with bolts and nuts. A thermocouple was inserted through a small hole at the left end to collect the temperature changes at the hot spot during the solidification process. In order to collect the load changes, a force sensor was also 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 thermal baffles was 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. As the solidification proceeds, the dendrites come into contact with each other to form a continuous framework, the heat can more easily transfer radially along the solid phase, and the temperature difference between the center and the edge would 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 the dendrite coherence temperature, denoted as T_{coh} .

The prediction of the hot tearing susceptibility ofAl-5Cu-*x*Sc alloys was based on the Cracking Sensitivity Coefficient (CSC*)* model established by Clyne and Davies[5]. 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, the sufficient liquid phase enables effective release of contraction stresses and feeds intergranular separations, therefore hot tearing would hardly occur. The vulnerable time, denoted as t_V , is defined as the duration spanning from f_S 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 ratio of t_V to t_R , and its calculation formula is as follows:

$$CSC = \frac{t_V}{t_R} = \frac{t_{0.99} - t_{0.9}}{t_{0.9} - t_{0.4}} \tag{0.1}$$

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

The solid phase fraction of the alloy is calculated by the Newton's baseline method, and its formula is as follows[26]:

$$f_S = \frac{\int_{t_L}^{t}\left[\left(\frac{dT}{dt}\right)_{cc} - \left(\frac{dT}{dt}\right)_{bl}\right]dt}{\int_{t_L}^{t_S}\left[\left(\frac{dT}{dt}\right)_{cc} - \left(\frac{dT}{dt}\right)_{bl}\right]dt} \tag{0.2}$$

Where cc represents the cooling curve, bl represents the baseline, and t_L , t_S are the start and end moments of solidification.

3 Results and discussion

3.1 Study on the stress-strain characteristics of the liquid film between two single grains

The liquid film theory postulates that during terminal solidification, decreasing temperature reduces the amount of liquid phase, leading to progressive thinning of intergranular films. Strain concentration occurs at residual hot spots, and when the accumulated strain exceeds a critical threshold, the film rupture occurs, 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.[27], 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 Figure 3.

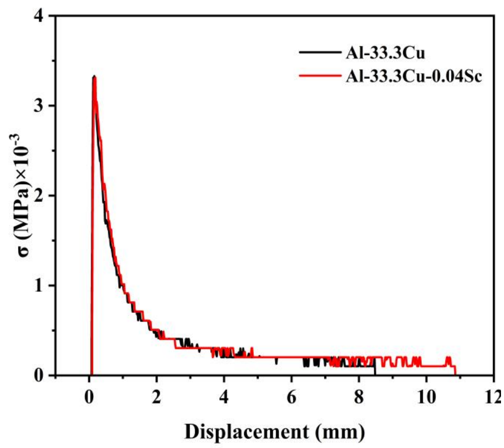

Fig. 3: Stress-displacement curves of alloy liquid films

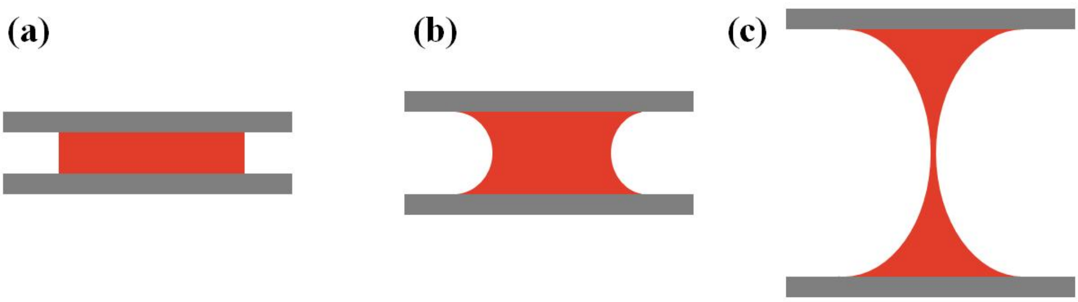

Fig. 4: Schematic diagram of morphological changes during the stretching alloy liquid films

Fig. 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 during initial loading. Plastic instability stage: after the stress reaches the limit value and 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 Figure 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 larger than that of the Al-33.3Cu liquid film (8.45 mm). During terminal 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, more time could be provided for the liquid feeding, thereby reducing the hot tearing susceptibility of the alloy.

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 is, the higher the corresponding f_S will be, which can well resist the stress generated by solidification shrinkage and the lower the hot tearing susceptibility will be. 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 occurred, 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-Cu 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.

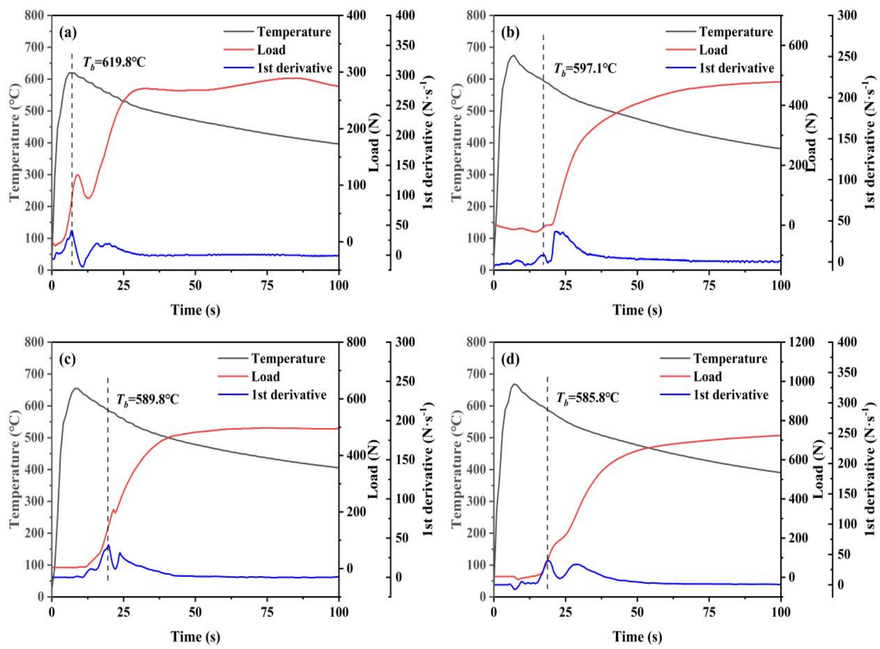

Fig. 5: Load and temperature curves of the “T” mold experiment for Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03

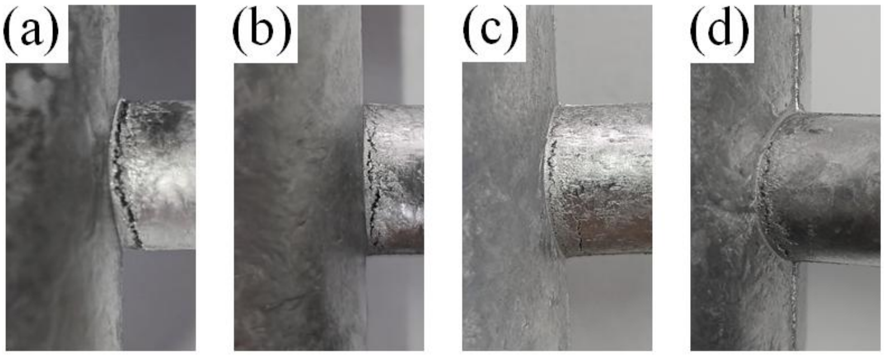

Fig. 6: Macroscopic cracks of Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03

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). High T_{coh} means early formation of the solid skeleton, shortens the effective liquid feeding duration, and extends the stage without feeding since the liquid is divided into isolated molten pools. Meanwhile, the earlier the solid phases come into contact with each other, the greater the stress accumulation during solidification shrinkage will be, resulting in an 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.

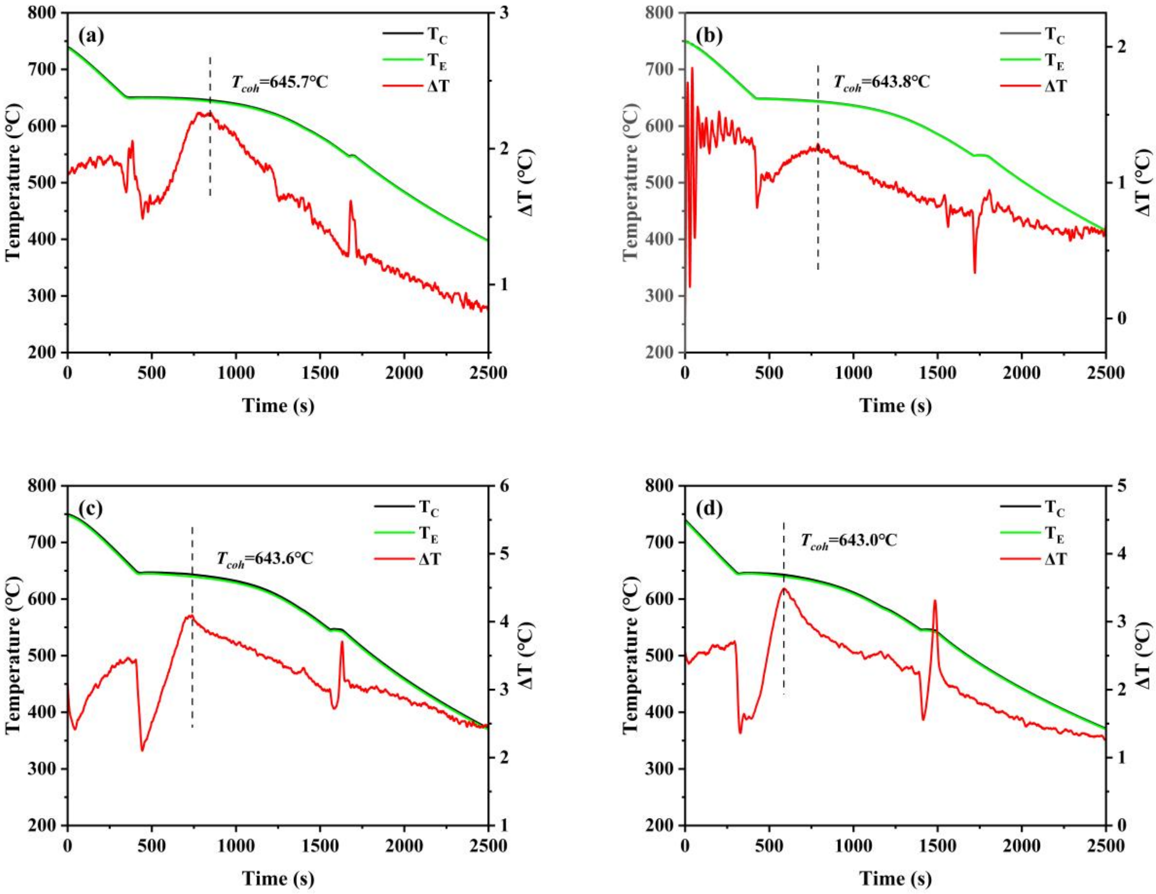

Fig. 7 Differential thermal analysis and T_{coh} of Al-5Cu-*x*Sc alloys: (a) *x*=0; (b) *x*=0.01; (c) *x*=0.02; (d) *x*=0.03

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. During the solidification, when the solid phase precipitates or the phase transformation occurs, the heat is released, and the cooling rate will decrease, thereby appearing an exothermic peak on the first derivative of the cooling curve. And the baseline represents the solidification process without phase transformations. 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) eutectic. From the first derivative curves of the cooling curves, there is no obvious precipitation peak of the Sc-containing phase. The minor Sc addition results in comparable intensities between the precipitation peak of the Sc-containing phase and impurity peak, while the solidification temperature range of the alloys remains largely unaffected (liquidus: approximately 653 °C; solidus: approximately 542 °C).

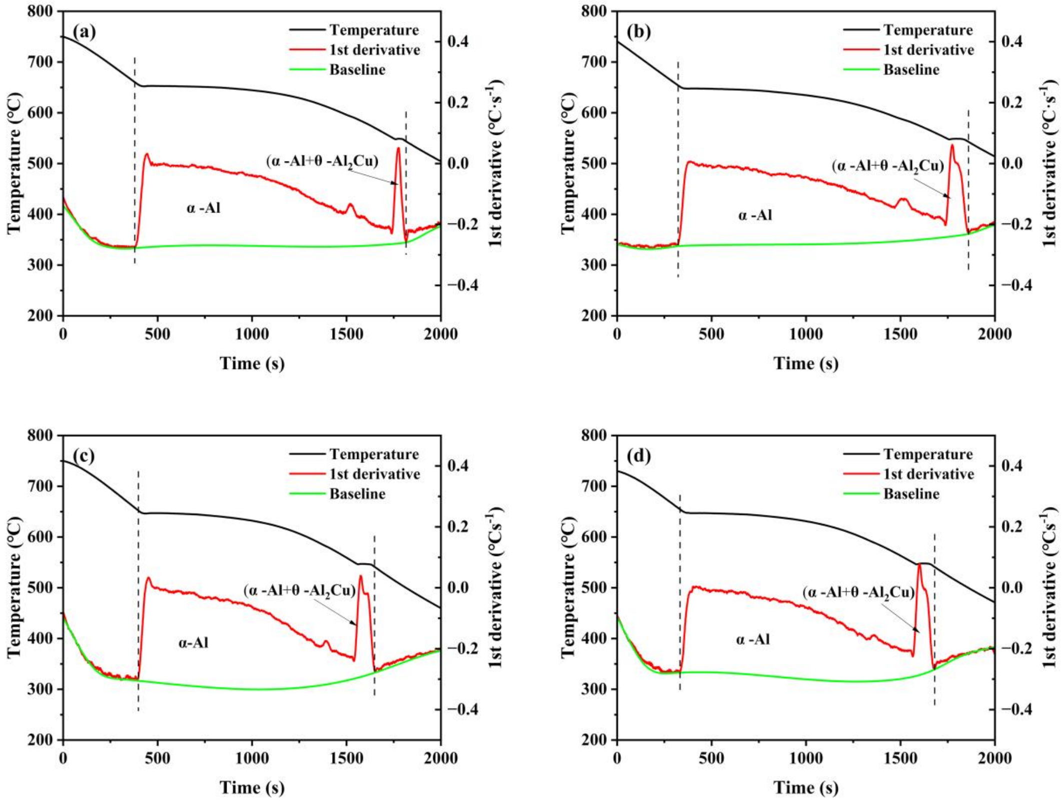

Fig. 8: Cooling curves, first derivative curves and baselines of Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03

Table 2: Phase precipitation temperatures of Al-5Cu-xSc alloy

Alloy	Precipitation Temperature (℃)	
	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

The CSC calculated via Equations (0.1) and (0.2) 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.

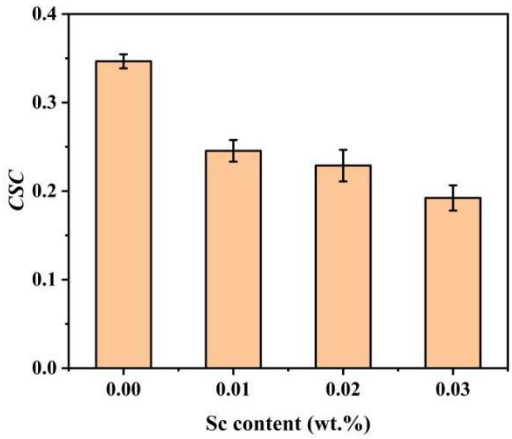

Fig. 9: CSC of Al-5Cu alloys with different Sc contents

3.4 Numerical simulation analysis of the 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 Fig. 10-11. 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 simulation result of the stress field during the solidification has well proved this point. 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.

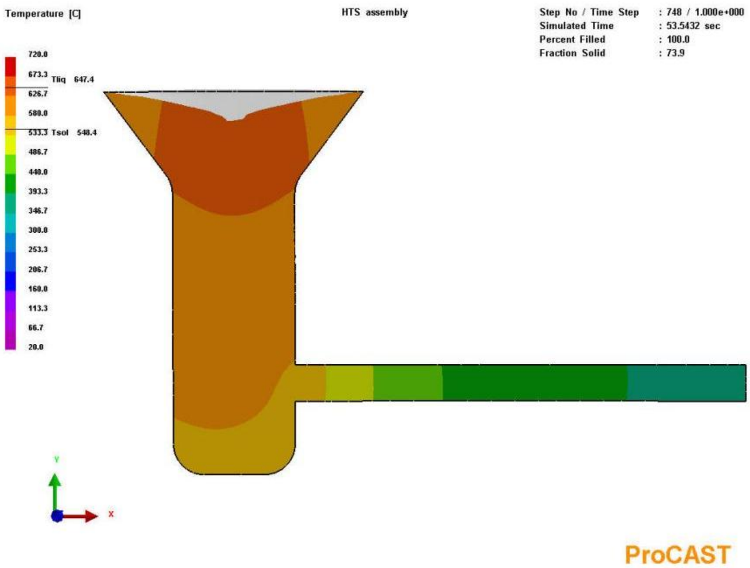

Fig. 10: Numerical simulation of the temperature field during the solidification of Al-5Cu-0.03Sc alloys

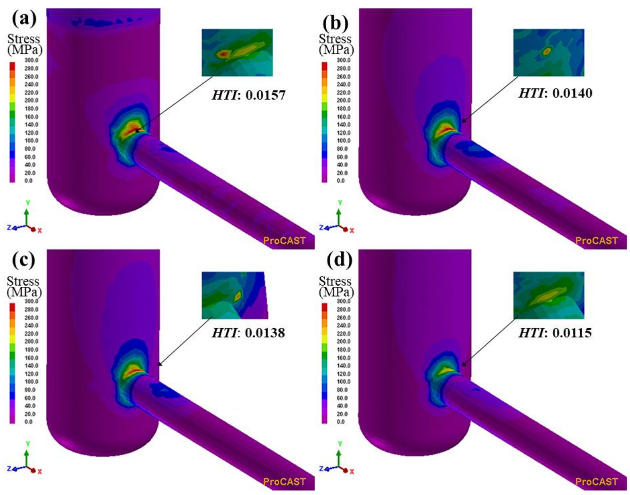

Fig. 11: Numerical simulation of stress field and HTI of Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03

3.5 Microstructure analysis

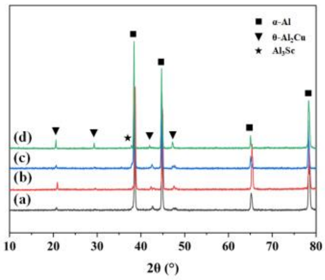

Fig. 12: XRD results of Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03

The XRD test results of Al-Cu alloys with different Sc contents are shown in Figure 3. 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 0.03%, a small amount of Al_3Sc is detected in the sample, while its diffraction peak is not obvious when the Sc content is low.

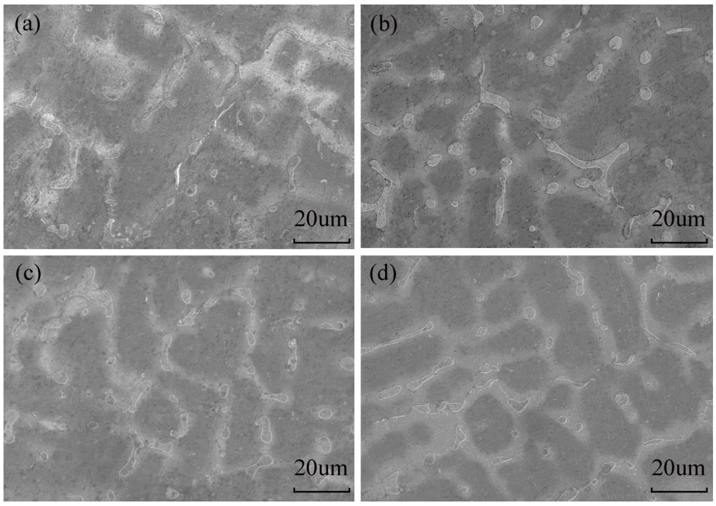

Fig. 13: SEM images of Al-5Cu-xSc alloys: (a) x=0; (b) x=0.01; (c) x=0.02; (d) x=0.03

The SEM images of the alloy are shown in Fig. 4. In Fig. 4, α-Al appears as dark gray dendrites, and light gray (α-Al+θ-Al_2Cu) eutectics are distributed between the α-Al dendrites. According to the equilibrium Al-Cu phase diagram, the minimum Cu content for eutectic reaction is 5.7 wt.%. 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.4 (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 Fig.4 (b-d) that the dendrites in the Sc-containing alloys are relatively fine, and there are more fine circular or short rod-shaped θ-Al_2Cu in the gaps of the dendrites. The addition of Sc refines the primary α-Al dendrites, resulting in shorter and more feeding channels between the liquid films during terminal solidification, thereby promoting liquid feeding. On the other hand, 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.

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 terminal solidification of Al-5Cu alloys. Combining with "T" 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 following conclusions are obtained:

(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 ℃ to 585.8 ℃, accompanied by flatter load curves during solidification. The dendrite coherence temperature decreases from 645.7 ℃ to 643 ℃ and the CSC decreases from 0.347 to 0.192, effectively shortening the vulnerable time difficult to feed. 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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Conflicts 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.

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