EFFECT OF DEGASSING AND GRAIN REFINEMENT ON HOT TEARING TENDENCY IN Al8Si3Cu ALLOY

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Abstract

The effect of melt quality on hot tearing susceptibility of Al8Si3Cu alloy was examined under six different conditions, by using a traditional T-shaped mold. Grain refinement was carried out by two different modifiers: AlTi5B1 and Al3B. For each test, samples were cast before and after degassing of melt. Therefore, a new hot tearing tendency index was developed by both bifilm calculations and porosity that occurred in the middle of T-zone of casting parts. Results indicated that hot tearing of cast aluminum alloys was a complex phenomenon, and bifilms play a major role, especially by compensating for shrinkage and consequently contributing to the inconsistencies in results.

Keywords: *casting, aluminum alloys, grain refining, simulation, hot tearing*

Introduction

Hot tearing is a casting defect in which a crack is visible on the surface of the casting at the end of solidification. Hot tearing in aluminum castings has been an issue that has been very difficult to address by foundrymen.[1] The first studies about this defect were conducted more than eighty years ago.[2] Since then, many mold types have been developed and used to examine the occurrence of hot tearing.[3–10] Initially, molds for hot tearing experiments were quite simple, but recently molds have become more complex to better understand the hot tearing phenomena. It is known that hot tearing occurs in the mushy zone, particularly in the hot spot of a poorly designed cast part where lack of feeding leads to uniaxial tension of the remaining liquid that causes tearing.[1] Some researchers have used a mold that has a load cell to measure the strength in the hot spot areas.[11–13] In this way, the stress needed to initiate hot tear in aluminum alloys was measured. Bichler and Ravindran studied hot tearing in Mg alloys. They used T-shaped mold and AZ91D alloy in their study. They claimed that hot tearing can occur at a low stress (∼ 12 MPa) if there is a shrinkage porosity to initiate hot tearing.[14] Rathi et al.[15–17] studied the performance of Al5TiB1 grain refiner to minimize hot tearing in Al7Si3Cu alloy. They found that porosity can be present around the hot tearing area because of unnecessary liquid at the solidified area.

Some studies focused on analytical modeling of hot tearing in aluminum alloys where three different approaches were proposed as the hot tearing criteria: strength,[18–22] strain[20,23,24] and strain rate,[25–28] although other criteria have also been proposed.[3,29,30] It is widely believed that these three criteria can indeed be used to predict hot tearing. Nevertheless, there remain some important observations that have not been completely explained by the existing criteria: (1) hot tearing does not always occur under the same conditions, and therefore, results can seldom be replicated, (2) hot tearing is not common to all alloys, and is severe for particular alloys and (3) occurrence of hot tearing seems to be completely random. Hence, results in the literature show that hot tearing formation still needs to be evaluated in detail, and an effort to shed light on these three issues should be made.

Two of the most commonly used molds to examine hot tearing are constrained rod casting (CRC) and T-shaped molds. Li[12] developed a formulation to calculate hot tearing quantitatively by using CRC mold, by defining hot tearing sensitivity (HTS) as:

$$\mathrm{HTS} = \sum (L_i \cdot C_i) \qquad \text{Eqn. 1}$$

where L_i is the arm code of CRC mold (from 1 to 4 for bars from bottom to top) and C_i is hot tear severity based on the crack characteristics observed on bars. It should be noted that there are several formulations used to calculate HTS for the CRC mold in the literature.[31–34] However, there is no formulation to quantify hot tearing in T-shaped molds. In the present study, a new approach was made to measure hot tearing degree (HTD) quantitatively for T-shaped mold. By using this new approach, the effect of degassing and grain refining on hot tearing formation in A380.1 alloy has been investigated.

Experimental Procedure

The chemical composition of A380.1 used in the experiments is given in Table 1. In Table 2, the compositions of the grain refiners are provided.

The charge was melted in a SiC crucible by using an electrical furnace with a capacity of 22 kg and 4 kW power. In the first trials, the castings were made without any additions, and this is referred as "as-received castings." The pouring temperature was 740 °C for all experimental trials. Then, two different melts were prepared where AlTi5B1 was added to one and Al3B was added to the other charge. All castings were carried out by using T-shaped preheated (250 °C) die mold. The dimensions of the T-shaped mold are given in Figure 1. The mold was tilted about 45° during pouring to decrease the influence of turbulence during filling.

Table 1. Chemical Composition (in wt%) of A380.1 Alloy

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
A380.1	8.14	0.64	3.12	0.44	0.22	0.49	0.02	Rem.

Table 2. Chemical Composition (in wt%) of Master Alloys

Master alloy	Ti	Sr	B	Fe	Si	Ca	Al
AlTi5B1	5.0	–	1.0	0.2	0.2	–	Rem.
Al3B	–	–	3.5	0.3	0.2	–	Rem.

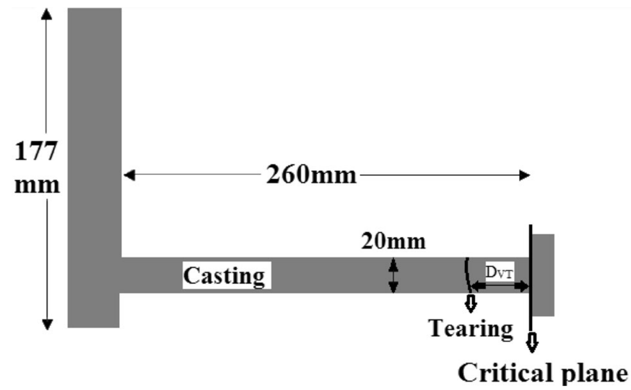


Figure 1. Dimension of T-shaped mold where thickness is 20 mm.

For each test, samples were produced before and after degassing of the melt to determine the effect of degassing. For the non-degassed melt, castings were made after 5 min of holding when the pouring temperature was reached. For the degassed melt, argon was purged through the melt for 20 min. Then, the grain refiner was added (1/1000 ratio). The liquid metal was held for 5 min, and then, the castings were completed. All experimental conditions were repeated three times for statistical reliability.

Hot tearing tool of MagmaSoft casting simulation software was used for predetermination of the hot tearing susceptibility. Cast parts were first visually examined to determine whether there was any hot tearing. Then, for the hot-torn parts, scanning electron microscopy (SEM) examination was carried out on the cross sections. In addition, the size and location of the hot tearing was recorded.

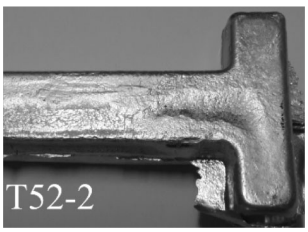
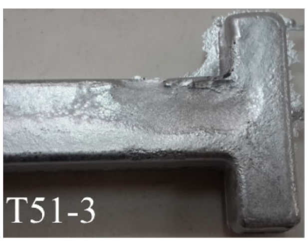
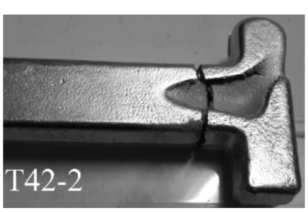
Result and Discussion

Five different severity levels of tearing were determined taking into account the surface sink and tearing simultaneously. These five levels are given Eqn. 2. It was determined that a fixed number was needed to provide the effect of surface sink. This value was fixed to be three (3). On the other hand, the distance of tearing from critical plane of the mold was a large value and so it was considered that one tenth of the number should be used. Data gathered from all the tests were used to create a formulation in a way to provide a quantitative value (HTD) for T-shaped mold. The proposed formulation is:

$$\mathrm{HTD} = S_{\mathrm{T}} \times (F_{\mathrm{SC}} + D_{\mathrm{VT}}/10) \qquad \text{Eqn. 2}$$

where S_{T} is the severity of hot tearing, F_{SC} is the surface sink factor (3) and D_{VT} is the distance of vertical tearing from critical plane. The severity levels are described in detail in Table 3.

Table 3. Severity Levels of Hot Tearing for T-shaped Mold

Images of hot tearing zones	Severity	Description
	2	A surface sink with no crack on it
	4	A surface sink with short crack(s)
	6	A surface sink with long crack(s)
	10	A surface sink with crack(s) or no crack(s) and vertical tearing on a different zone
	30	A surface sink with long and/or short crack(s) or no crack(s) and vertical tearing on the same zone

The idea behind the use of a value for the severity of the surface sink is simply due to the fact that a perfect surface sink would only occur in the absence of bifilms.[35] In the presence of bifilms, the unraveling will cause the pore formation which compensates for the solidification shrinkage.[35] Alternatively, when there is no bifilm and no feeding, the remaining liquid would contract the solid phase that surrounds it and the strong force generated by the solid/solid contraction will lead to surface sink.[35]

It is well known that A380.1 alloy has a long freezing range (55 °C) and two different eutectic points during solidification: α (Al) + Si eutectic transformation occurs at 577 °C and the remaining liquid in the casting transforms to eutectic α (Al) + Cu at approximately 530 °C. The last liquid to solidify is an important factor for hot tearing in aluminum alloys. During Al–Cu eutectic transformation, tearing or cracking can form. Hence, hot tearing formation

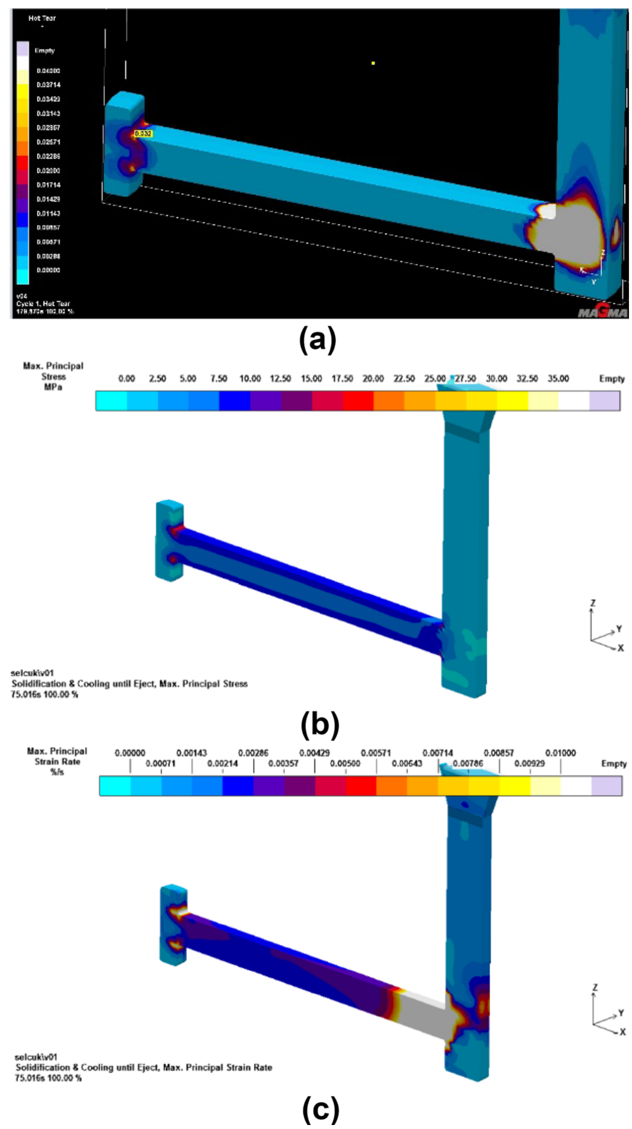


Figure 2. Result of (a) hot tearing, (b) stress, (c) strain obtained from MagmaSoft.

is seen widely in aluminum alloys which include copper such as A380.1 alloy. This was first recorded by Clyne and Davies.[3]

Casting simulations were conducted on this alloy to understand the mechanism of hot tearing. The results of computer simulations for hot tear are presented in Figure 2, which shows that the critical area with a hot spot that causes hot tearing is at the intersection of the T part and horizontal part. This region was taken as a datum plane in calculations of hot tearing for the present work. The principal stress (Figure 2b) occurs along the horizontal bar's top and bottom surfaces that acts upon the corners to generate a strain (Figure 2c).

Data from experimental studies were used to calculate the degree of hot tearing that was given before in the experimental procedure section (Eqn. 2). HTD results are given in Figure 3. Results show that grain refinement plays an important role on hot tearing. HTD was reduced after adding each grain refinement for both no degassing and degassed conditions. These results are consistent with the results of Li,[13] Kamali,[36] Nadella[37] and Benny Karunakar.[38] Warrington and McCartney[39] observed the same effect of grain refinement on hot tearing but stated that if grain refiner were to be added in larger amounts, hot tearing would get worse. Rosenberg,[40] however, claimed that grain refinement has no effect on hot tearing. Similarly, D'Elia[41] also found that addition of various amounts of Ti grain refinement did not affect hot tearing. However, the transition from dendritic to equiaxed microstructure had eliminated hot tearing for B206.[42] Sadayappan[43,44] used magnetic field to control the segregation and fluid flow. It was observed that directional solidification had led to increased hot tearing. Hence, the literature is rich with contradictory results.

The observations summarized above can be unified under a scientific explanation. As shown in Figure 3, grain refiner does reduce hot tearing degree. Moreover, Al3B grain refiner, which is Ti-free, decreases hot tearing degree more than AlTi5B1 grain refiner. It can be speculated that the beneficial effect of grain refiner is due to the change in microstructure which is transformed from columnar to equiaxed. This transformation increases feeding, which

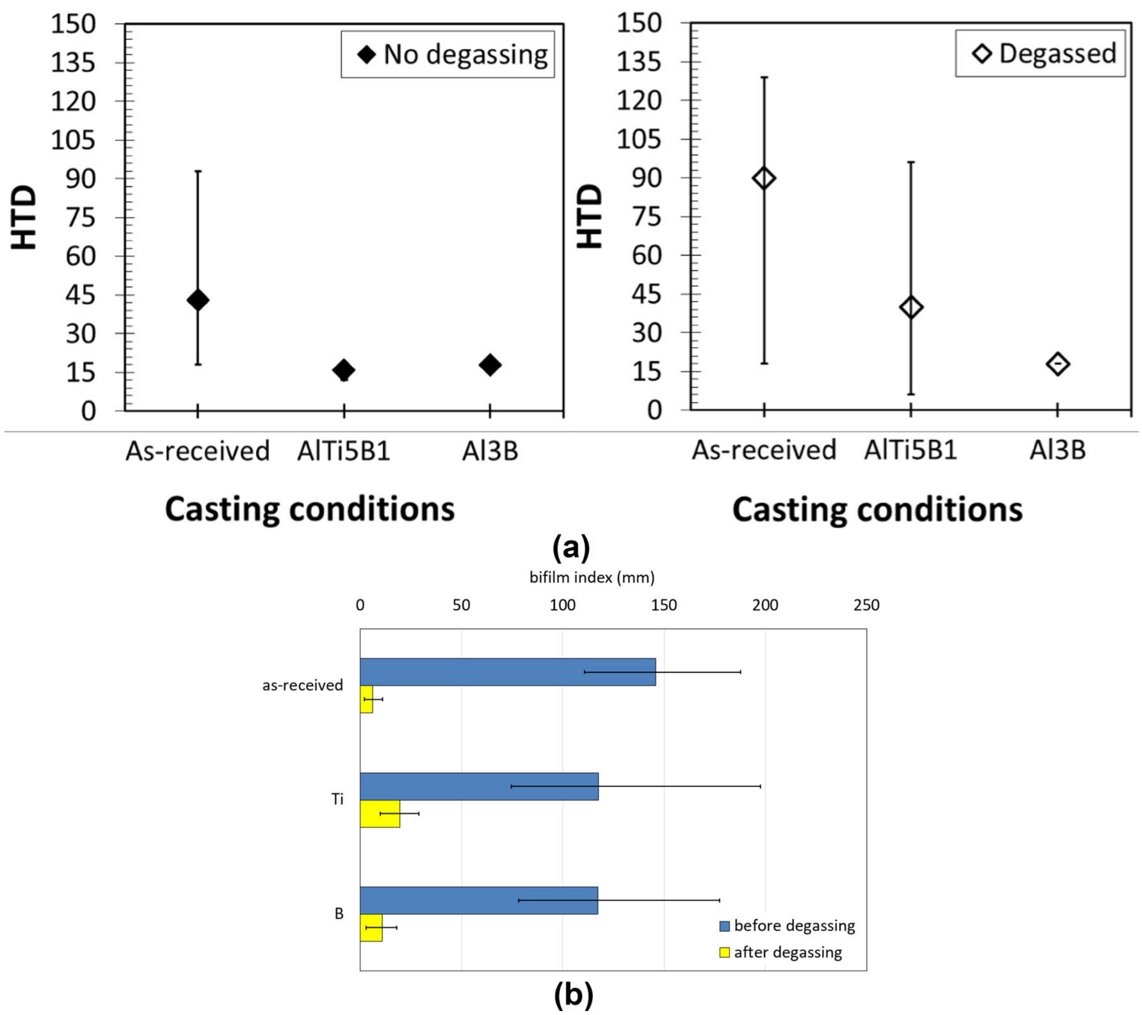


Figure 3. Results of (a) HTD, (b) bifilm index showing the quality of the melts.

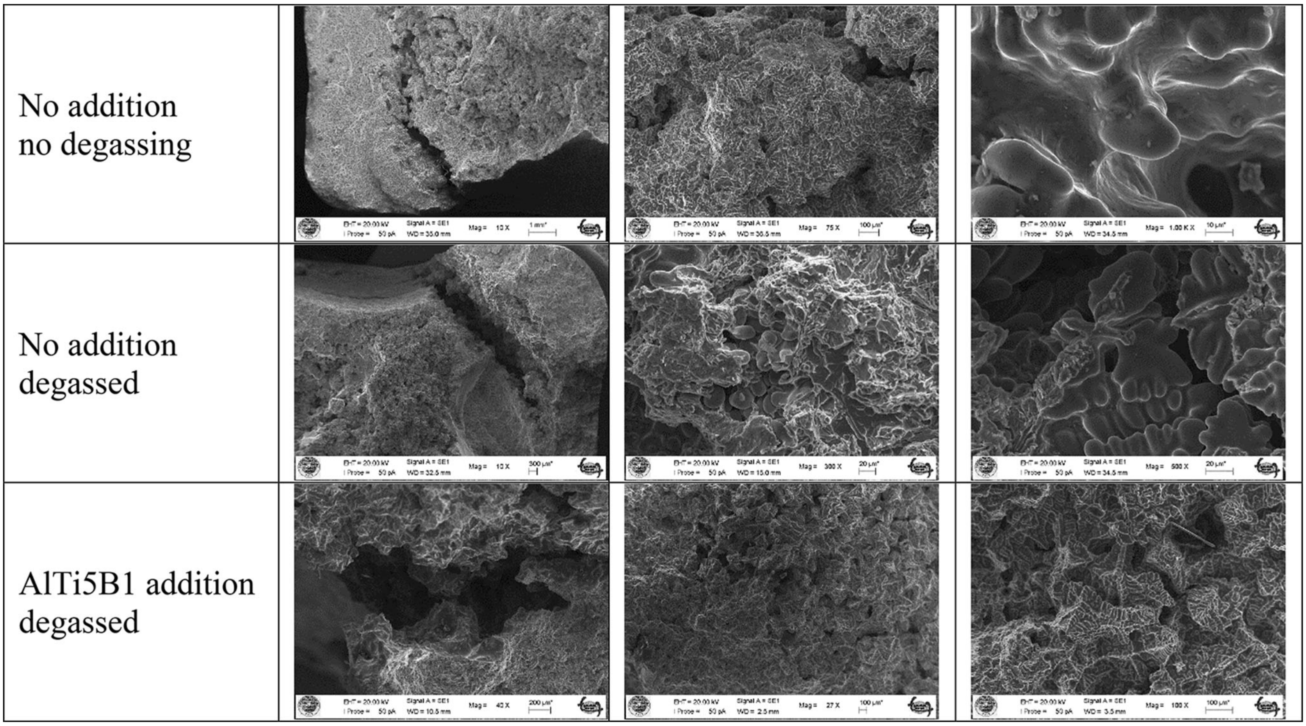


Figure 4. SEM images of hot tearing surfaces.

will of course help reduce hot tearing or cracking formation.

Bifilm index results are summarized in Figure 3b. Bifilm is a folded oxide which occurs mainly by turbulence.[45,46] It can be seen that melt quality was significantly improved after degassing. From an average of 120–150 mm, the values were dropped down to 10–20 mm, indicating that rising bubbles in liquid aluminum removed bifilms from the melt efficiently. In the absence of bifilms, the shrinkage causes the surface sink and under no other circumstances porosity may form. Therefore, in this work, when the bifilm index was high, pores were formed to compensate contraction, and thus, no tearing was observed.

It is well known that Ti has fading effect.[47] Therefore, the efficiency of grain refining may vary significantly. The heterogeneity of microstructure with various long primary arms and secondary arms is possible under these circumstances. On the other hand, it was Tondel et al.[48] who initially showed that Ti-free grain refinement with B can lead to more globular dendrites indicating homogeneous structure. Similarly, Dispinar[49] had shown that more localized pores were observed when B grain refinement was used. Dispinar[49] stated that bifilms were unable to open or unravel under these circumstances. Thus, the distributed pores in Ti grain refinement compared to the localized pores in B grain refinement were also related to the bifilms.

The severity of solid contraction can easily be seen with large surface sinks on the edges of the cross sections of samples (Table 3). It is important to note that when Al3B was used, no tearing was observed whether the melt was degassed or not. However, non-treated alloy was subjected to tearing in both cases. For Ti grain refined alloy, tearing was observed only after degassing. Similar results were reported in the literature.[13,36–38]

SEM images of fracture surfaces are presented in Figure 4. On all surface of hot tearing regions, oxide bifilms were observed. The presence of oxides on hot tearing surfaces can explain the nucleation of cracks that result in hot tears. If there is no inclusion to initiate a crack, it is impossible that hot tearing takes place; thus, casting will have surface sinks because of solidification shrinkage.

Energy-dispersive X-ray (EDX) analysis was carried out on fracture surfaces of hot tearing regions (Table 4). Bifilms are generally observed to be the initiator of hot tearing. Since the bonding between the folded oxide surfaces is zero, with the existence of air gap in between them, the opening or unraveling of bifilms can be facilitated easily by the solidification contraction. Thus, the same phenomenon occurs for hot tearing. Any bifilm that lies along the stress or strain applied during solidification can aid the separation of the liquid, i.e., hot tearing. This is one of the reasons why hot tearing observations in the literature were so inconsistent. The heterogeneity of microstructure by Ti grain refinement can aid bifilm unraveling as was stated earlier by Dispinar.[49]

Table 4. EDX Analysis of Hot Tearing Surfaces

Element	Series	Unn. C (wt%)	Norm. C (wt%)	Atom. C (at.%)	Error (%)
Aluminum	K-series	68.55	69.88	64.46	3.3
Oxygen	K-series	14.91	15.20	23.64	2.3
Silicon	K-series	9.68	9.87	8.75	0.4
Copper	K-series	3.13	3.19	1.25	0.1
Magnesium	K-series	1.82	1.86	1.90	0.1
Total		98.09	100.00	100.00	

The sum of element content is not 100%, because its due to the error%

Conclusion

A new metric to quantify the extent of hot tearing in a T-shaped mold was developed in this study. It is the first time that such a numerical quantification is presented for this particular mold design. The formula is given as:

$$HTD = S_T \times (F_{SC} + D_{VT}/10)$$

where S_T is the severity of hot tearing, F_{SC} is the surface sink factor and D_{VT} is the distance of vertical tearing from critical plane.

The effect of different grain refiners on hot tearing was investigated in the present study for A380.1 alloy. It was understood that grain refiner plays an important role to reduce hot tearing severity, only because they affect the unraveling of bifilms. Al3B grain refiner that is Ti-free has a significant effect on hot tearing which drops hot tearing tendency by 60–83%, while AlTi5B1 grain refiner has around 50–60% efficiency.

For hot tearing to occur, a crack initiator has to preexist during solidification. It was determined that this crack initiation in aluminum alloys can be traced back to oxide bifilms. If there are many bifilms in the liquid, they will form porosity to compensate the shrinkage and no tearing would occur.

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REFERENCES

1. J. Campbell, *Castings : [The New Metallurgy of Cast Metals]* (Butterworth Heinemann, Oxford, 2003)
2. J. Verö, The hot-shortness of aluminum alloys. Met. Ind. **48**, 431–494 (1936)
3. T. Clyne, G. Davies, A quantitive solidification test for casting and an evaluation of cracking in aluminium-magnesium alloys. Br. Foundrym. **68**, 238–244 (1975)
4. M.O. Pekguleryuz et al., Hot tear susceptibility of aluminium–silicon binary alloys. Int. J. Cast Met. Res. **23**(5), 310–320 (2010)
5. M. Pokorny et al., Prediction of hot tear formation in magnesium alloy permanent mold casting. Int. J. Metalcasting **2**(4), 41–53 (2008)
6. A. Singer, P. Jennings, J. Inst. Met. **73**, 197 (1947)
7. D. Warrington, D.G. McCartney, Cast Met **2**(3), 202–208 (1989)
8. S. Li, D. Apelian, Hot tearing of aluminum alloys a critical literature review. Int. J. Metalcasting **5**(1), 23–40 (2011)
9. S. Li, D. Apelian, K. Sadayappan, Hot tearing in cast Al alloys: mechanisms and process controls. Int. J. Metalcasting **6**(3), 51–58 (2012)
10. G. Sigworth, Hot tearing of metals. Trans. Am. Foundrym. Soc. **104**, 1053–1062 (1996)
11. S. Li, *Hot Tearing in Cast Aluminum Alloys: Measures and Effects of Process Variables, in Materials Science and Engineering* (Worcester Polytechnic Institute, Worcester, 2010)
12. S. Li, K. Sadayappan, D. Apelian, Characterisation of hot tearing in Al cast alloys: methodology and procedures. Int. J. Cast Met. Res. **24**(2), 88–95 (2011)
13. S. Li, K. Sadayappan, D. Apelian, Role of grain refinement in the hot tearing of cast Al-Cu alloy. Metall. Mater. Trans. B **44**(3), 614–623 (2013)
14. L. Bichler, C. Ravindran, Investigations on the stress and strain evolution in AZ91D magnesium alloy castings during hot tearing. J. Mater. Eng. Perform. **24**(6), 2208–2218 (2015)
15. S.K. Rathi, A. Sharma, M. Di Sabatino, Performance of Al–5Ti–1B master alloy after ball milling on minimizing hot tearing in Al–7Si–3Cu alloy. Trans. Indian Inst. Met. **70**(3), 827–831 (2017)
16. S.K. Rathi, A. Sharma, M. Di Sabatino, Effect of mould temperature, grain refinement and modification on hot tearing test in Al-7Si-3Cu alloy. Eng. Fail. Anal. **79**, 592–605 (2017)

17. S.K. Rathi, A. Sharma, M. Di Sabatino, Influence of annealing of Al-5Ti-1B master alloy on hot tearing of cast Al-7Si-3Cu alloy. in *Key Engineering Materials*, ed. by J.W. Jung (Trans Tech Publications, 2017)
18. C. Dickhaus, L. Ohm, S. Engler, AFS Transaction **101**, 677–684 (1994)
19. D. Lahaie, M. Bouchard, Metall. Mater. Trans. B **32B**, 697–705 (2001)
20. I. Novikov, *Goryachelomkost tsvetnykh metallov i splavov (Hot shortness of non-ferrous metals and alloys)* (Nauka, Moscow, 1966)
21. W. Suyitno Kool, L. Katgerman, Mat Sci Forum **179**, 396–402 (2002)
22. J. Williams, A. Singer, J Inst Met **96**, 5–12 (1968)
23. B. Magnin et al., Mater. Sci. Forum **1209**, 217 (1996)
24. L. Zhao et al., Int J Cast Metals Res **13**(3), 167–174 (2000)
25. N.N. Prokhorov, Russ. Cast. Prod. **2**, 172–175 (1962)
26. M. Rappaz, J.M. Drezet, M. Gremaud, A new hot-tearing criterion. Metall. Mater. Trans. A Phys. Metall. Mater. Sci. **30**(2), 449–455 (1999)
27. F. Fasoyinu et al., Permanent mold casting of aluminum alloys A206. 0 and A535. 0. Trans. Am. Foundrym. Soc. **115**, 207 (2007)
28. F. Fasoyinu et al., Characterization of microstructures and mechanical properties of aluminum alloys 206.0 and 535.0 poured in metal molds. Trans. Am. Foundrym. Soc. **116**, 265 (2008)
29. U. Feurer, *Quality control of engineering alloys and the role of metals science* (Delft University of Technology, Delft, 1977)
30. L. Katgerman, JOM **34**(20), 46–49 (1982)
31. M. Pekguleryuz, P. Vermette, A study on hot-tear resistance of magnesium diecasting alloys. Trans. Am. Foundry Soc. **114**(114), 729–736 (2006)
32. M.O. Pekguleryuz, P. Vermette, Developing castability index for magnesium diecasting alloys. Int. J. Cast Met. Res. **22**(5), 357–366 (2009)
33. H. Kamguo Kamga et al., Hot tearing of aluminum–copper B206 alloys with iron and silicon additions. Mater. Sci. Eng., A **527**(27–28), 7413–7423 (2010)
34. G. Cao, S. Kou, Hot tearing of ternary Mg − Al − Ca alloy castings. Metall. Mater. Trans. A **37**(12), 3647–3663 (2006)
35. J. Campbell, *Complete casting handbook: metal casting processes, metallurgy, techniques and design* (Butterworth-Heinemann, Oxford, 2015)
36. H. Kamali, M. Emamy, A. Razaghian, The influence of Ti on the microstructure and tensile properties of cast Al–4.5Cu–0.3 Mg alloy. Mater. Sci. Eng., A **590**, 161–167 (2014)
37. R. Nadella, D. Eskin, L. Katgerman, Role of grain refining in hot cracking and macrosegregation in direct chill cast AA 7075 billets. Mater. Sci. Technol. **23**(11), 1327–1335 (2007)
38. D. Benny Karunakar et al., Effects of grain refinement and residual elements on hot tearing in aluminum castings. Int. J. Adv. Manuf. Technol. **45**(9–10), 851–858 (2009)
39. D. Warrington, D. McCartney, Hot-cracking in Aluminium Alloys 7050 and 7010-a Comparative Study. Cast Met. **3**(4), 202–208 (1991)
40. R.A. Rosenberg, M.C. Flemings, H.F. Taylor, Non-ferrous binary alloys hot tearing. AFS Trans. **69**, 518–528 (1960)
41. F. D'Elia, C. Ravindran, Poisoning in grain refinement of A319 aluminum alloy and its effect on hot tearing (10-065). Trans. Am. Foundrym. Soc. **118**, 83 (2010)
42. F. D'Elia, C. Ravindran, Effect of Ti-B grain refiner on hot tearing in permanent mold cast B206 aluminum alloy. Trans. Am. Foundrym. Soc. **117**, 139 (2009)
43. M. Sadayappan et al., Influence of marangoni convection on hot tearing in aluminum alloys. in *Transactions of the American Foundry Society and the One Hundred Fifth Annual Castings Congress* 2001
44. M. Sadayappan et al., Effect of melt processing and magnetic field on the hot tearing of Al-Cu alloy A 201. in *Transactions of the American Foundry Society and the One Hundred Sixth Annual Casting Congress* 2002
45. D. Dispinar, J. Campbell, Critical assessment of reduced pressure test. Part 2: quantification. Int. J. Cast Met. Res. **17**(5), 287–294 (2004)
46. D. Dispinar, J. Campbell, Critical assessment of reduced pressure test. Part 1: porosity phenomena. Int. J. Cast Met. Res. **17**(5), 280–286 (2004)
47. P.L. Schaffer, A.K. Dahle, Settling behaviour of different grain refiners in aluminium. Mater. Sci. Eng., A **413**, 373–378 (2005)
48. P.A. Tondel, G. Halvorsen, L. Arnberg, *Grain-Refinement of Hypoeutectic Al-Si Foundry Alloys by Addition of Boron Containing Silicon Metal*. Light Metals 1993, ed. S.K. Das. 1992, Warrendale: Minerals, Metals & Materials Soc
49. D. Dispinar et al., Influence of hydrogen content and bi-film index on feeding behaviour of Al-7Si. in *138th TMS Annual Meeting, Shape Casting: 3rd International Symposium*, San Francisco, California, USA, (February 2009). 2009