detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

IMPACT OF CHEMICAL COMPOSITION ON HOT TEARING IN SECONDARY WROUGHT ALUMINUM ALLOYS

Emidio Giansante *, Giulio Timelli and Alberto Fabrizi

Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, Vicenza, Italy

Article Info:
Received:
6 May 2024
Revised:
11 July 2024
Accepted:
20 August 2024
Available online:
8 October 2024

Keywords:
Hot tearing
Secondary wrought Al alloys
Thermodynamic simulations

ABSTRACT

Hot tearing represents one of the most detrimental defects in metal castings and it is a key parameter for evaluating alloy castability. Hot tearing in aluminum alloys has gained attention from several research groups over the past century. To date, there are several theories that aim to understand the mechanisms and identify the parameters affecting the formation of hot cracks. This study aims to evaluate the influence of chemical composition on the hot cracking index of eight commercial wrought alloys of 6xxx series (Al-Mg-Si alloys), produced from recycled scrap. First, a thermodynamic calculation software was used to determine the solidification path of the alloys under non-equilibrium conditions; subsequently, a pure theoretical criterion, the Kou model, was adopted to predict the susceptibility of hot tearing. The results reveal that variations in chemical composition affect the cracking index, and the alloy 6082 shows the higher vulnerability to hot cracking. Furthermore, minimizing the element content yields a minimum value of the hot cracking susceptibility index.

1. INTRODUCTION

Although aluminum (Al) is one of the most used non-ferrous metals (Padamata, Yasinskiy and Polyakov, 2021) its production from primary ores (e.g. bauxite) involves high energy consumption and large CO_2 emissions. Many governments have adopted regulations to encourage the production of aluminum from recycled scrap; in fact, secondary Al production demonstrates notable economic and environmental advantages compared to primary production (D'Errico and Mattavelli, 2017) such as an energy saving estimated at approximately 90%, a reduction in CO_2 emission close to 80% and a lower amount of solid waste (Cui and Roven, 2010).

Among the aluminum alloys, wrought ones are the primary choice to replace steel components due to their high strength-to-weight ratio, low density, and recyclability. The wrought alloys of 6XXX series (Al-Mg-Si alloys) offer an optimal combination of properties, exhibiting strength comparable to the 2XXX (Al-Cu) or 7XXX (Al-Zn) series alloys but higher workability, weldability, and corrosion resistance (Graf, 2021). However, wrought alloys exhibit poor tolerance to impurities and, as a result, their production from the recycled scrap is significantly limited as only a smaller share of the collected scrap is used to produce the alloys. Moreover, it is often necessary to adjust the chemical composition by diluting with large quantities of primary aluminum ingots (Van den Eynde, et al., 2022).

Another drawback for wrought alloys is their susceptibility to hot tearing, a macroscopic defect related to the formation of macroscopic cracks during the final solidification stage, i.e. when the solid fraction reaches values between 85 and 95% (Li and Apelian, 2011).

Since the 1950s, several researchers have attempted to understand the mechanisms of hot tearing and develop predictive mathematical models (Eskin, Suyitno, and Katgerman, 2004). Clyne and Davies (Clyne and Davies, 1975), for example, proposed a criterion where the susceptibility to hot tearing is determined by the ratio of vulnerable time to recovery time. The "vulnerable time" is defined as the period during which the alloy transitions from 90% to 99% solid fraction. During this phase, liquid feeding is either impossible or highly restricted, preventing the filling of any developing cracks by the remaining liquid. Conversely, the "recovery time" is the time required for the alloy to transition from 60% to 90% solid fraction. According to Nyama (Niyama, 1977) and Feurer (Feurer, 1977), the formation of hot cracks occurs exactly when the solid dendritic network acts as a barrier for the remaining liquid phase, preventing it from flowing and healing the defects. Later, Rappaz-Drezet and Gremaud (Rappaz, Drezet, and Gremaud, 1999) developed a criterion deriving from a two-phase model that considers both the flow of the liquid and the deformation occurring during the solidification. Such models require a detailed experimental approach to study the solidifica-

* Corresponding author:
Emidio Giansante
email: emidio.giansante@phd.unipd.it

Detritus / Volume 29 - 2024 / pages 98-102
https://doi.org/10.31025/2611-4135/2024.19432

tion dynamics and mechanical stresses generated during component cooling. Finally, Kou (Kou, 2015) proposed a theoretical model without the use of experimental data. His method is based on Campbell's assumption that hot tearing is a uniaxial failure mechanism and the accumulated stress from the pressure drop must exceed a maximum value typical of the material. To evaluate the susceptibility to hot tearing, Kou has defined the following index:

$$HTS = \left| \frac{dT}{d(f_s^{\frac{1}{2}})} \right| \quad (1)$$

Where ds_f is the chosen solid fraction range and dT is the corresponding temperature interval. This criterion provides preliminary assessments of the tendency to hot cracking starting from thermodynamic simulations.

The trend in the coming years will be to increasingly reduce the use of primary alloys in favour of utilizing already available aluminum. Since the properties of aluminum alloys are influenced by the compounds present in their structure and, consequently, by the level of impurities, this study aims to use Kou's predictive criterion to evaluate the impact of chemical composition on the hot tearing resistance of 6XXX alloys. Special attention has been given to the effect of iron, as it is considered the major impurity in recycled aluminum alloys.

2. EXPERIMENTAL PROCEDURE

The chemical compositions of 8 commercial wrought alloys of 6xxx series were collected over two-year production period (2022-2023) and the average values with standard deviations are reported in Table 1. The Thermo-Calc simulation software was used to obtain curves of solid fraction vs temperature under non-equilibrium conditions by using the Scheil-Gulliver equation. For all the simulations, the initial temperature was set to 750°C with a step of 1°C; Figure 1 illustrates the resulting solidification curve of the 6060 alloy.

According to the Kou's criterion, the solid fraction range for hot tearing index was from 0.87 to 0.94. and the temperatures corresponding to the selected range were determined directly from the solidification curves. A regression analysis was conducted using Minitab, employing response surface regression to derive an equation that directly correlates the susceptibility index value with the alloying element content.

To assess the impact of iron on the hot tearing index, simulations were performed on the three alloys of greatest industrial significance – 6060, 6082, and 6005 – with varying iron contents. The specific levels examined were 0.4 wt%, 0.8 wt%, 1.0 wt%, and 1.5 wt% Fe.

3. RESULTS AND DISCUSSION

Considering the Kou indexes calculated for the average chemical composition (Figure 2), 6082 alloy exhibits the highest susceptibility to hot tearing, whereas the lowest index is observed for 6060 alloy. As it results from their solidification curves (Figure 3), 6082 alloy shows a larger temperature difference compared to alloy 6060 in the selected solid fraction range, confirming its greater tendency to hot tearing.

This result is consistent with practical outcomes from industry, where components manufactured with 6082 alloy commonly exhibit hot tearing cracks (Möller, Daswa and Govender, 2015).

The Kou indexes for the alloys with the upper and lower limits of the compositional range are shown in Figure 4. The values differ slightly from the indexes obtained for the average chemical composition. Considering the compositions of the upper limits, an increase of the hot tearing index is observed for most of the materials, while the indexes assume lower values in almost all cases for the alloys with minimum chemical composition.

The cases where the trend is not followed pertain to the 6061 and 6082 alloys. This deviation may be associated with reaching and surpassing the peak of maximum susceptibility. It is well-known that hot tearing susceptibility in many alloy systems follows the so-called lambda curves (Easton, St. John and Sweet, 2010; Campbell, 2015; Li and Apelian, 2011). Specifically, these curves illustrate how increasing alloying element content leads to a rise in hot tearing susceptibility up to a peak, after which susceptibility decreases. Figure 4 demonstrates that, for the 6061 alloy, increasing alloying element content corresponds to a progressive decrease in the index value. In contrast, for the 6082 alloy, an initial increase in the index is observed when transitioning from the minimum to the average composition. However, as the alloying content continues to rise, a subsequent decrease in hot tearing susceptibility is noted.

However, 6082 and 6061 alloys consistently remain the materials with the greatest susceptibility to hot tearing. Ex-

TABLE 1: Average chemical compositions of Al-Mg-Si alloys with standard deviations.

Alloy	Si %wt	Fe %wt	Mn %wt	Mg %wt	Cu %wt	Ti %wt	Zn %wt	Cr %wt	Al %wt
6060	0.449 ± 0.032	0.235 ± 0.018	0.045 ± 0.007	0.426 ± 0.038	0.030 ± 0.006	0.014 ± 0.003	0.040 ± 0.007	0.009 ± 0.003	Bal.
6061	0.667 ± 0.086	0.241 ± 0.019	0.081 ± 0.030	0.896 ± 0.064	0.209 ± 0.037	0.043 ± 0.018	0.042 ± 0.007	0.111 ± 0.037	Bal.
6082	0.922 ± 0.100	0.252 ± 0.019	0.505 ± 0.084	0.740 ± 0.080	0.048 ± 0.013	0.040 ± 0.013	0.046 ± 0.010	0.038 ± 0.039	Bal.
6005	0.638 ± 0.028	0.239 ± 0.022	0.072 ± 0.041	0.536 ± 0.037	0.053 ± 0.039	0.024 ± 0.009	0.042 ± 0.009	0.009 ± 0.002	Bal.
6005-A	0.631 ± 0.060	0.238 ± 0.020	0.198 ± 0.040	0.512 ± 0.039	0.055 ± 0.027	0.026 ± 0.011	0.041 ± 0.007	0.045 ± 0.030	Bal.
6063	0.517 ± 0.034	0.239 ± 0.018	0.046 ± 0.011	0.522 ± 0.041	0.032 ± 0.007	0.017 ± 0.006	0.042 ± 0.005	0.009 ± 0.002	Bal.
6101	0.445 ± 0.119	0.271 ± 0.082	0.040 ± 0.014	0.443 ± 0.128	0.035 ± 0.035	0.013 ± 0.006	0.036 ± 0.007	0.014 ± 0.022	Bal.
6101-B	0.447 ± 0.028	0.254 ± 0.022	0.047 ± 0.002	0.499 ± 0.022	0.033 ± 0.006	0.025 ± 0.002	0.044 ± 0.007	0.010 ± 0.002	Bal.

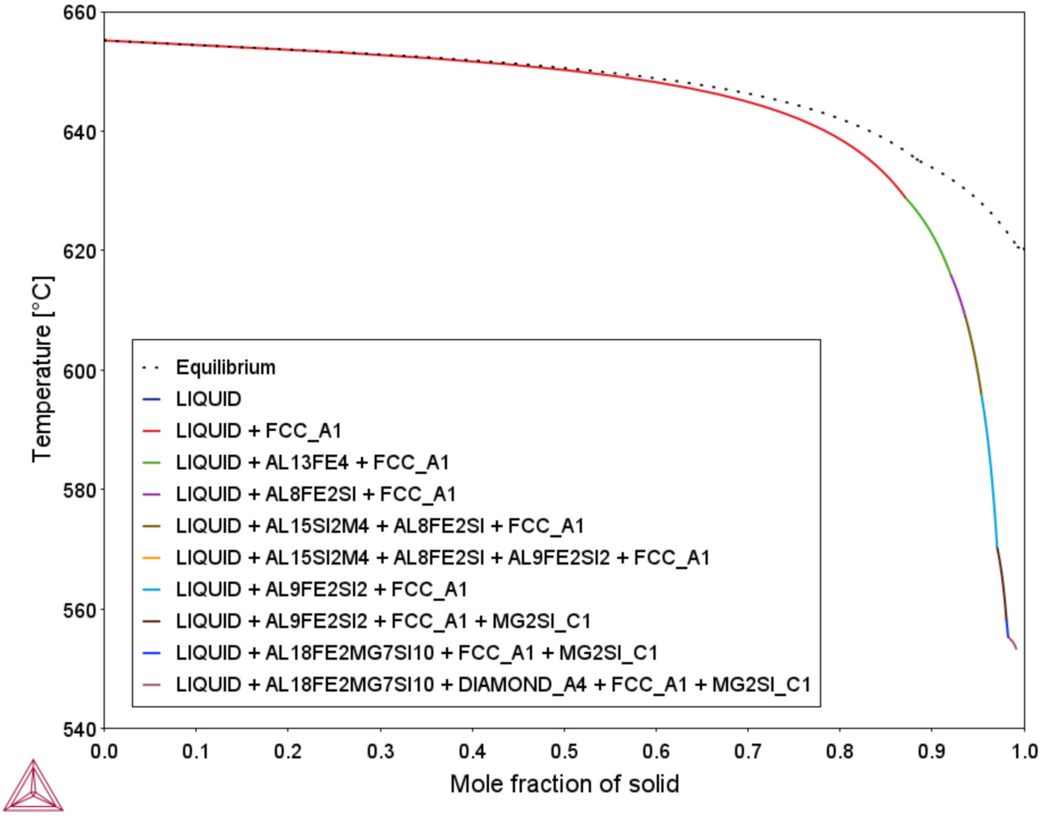

FIGURE 1: Solidification path of a 6060(average chemical composition) according to Scheil model.

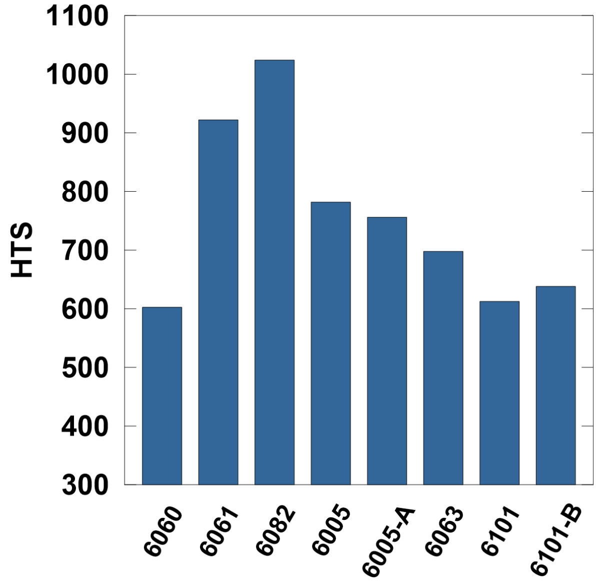

FIGURE 2: Kou's cracking index for different alloys.

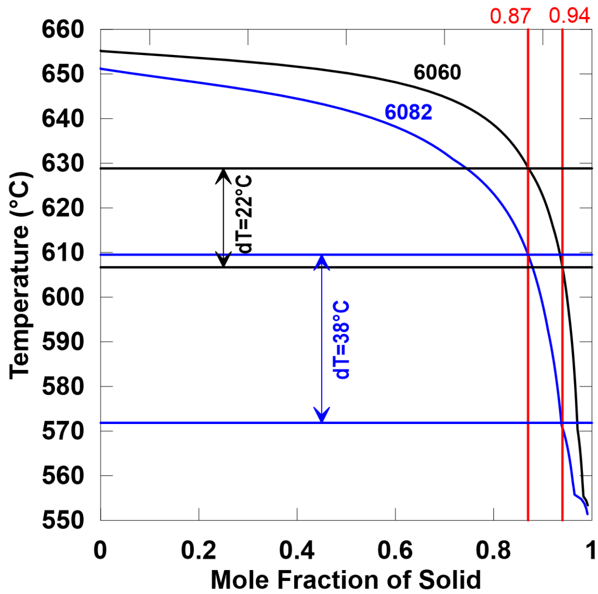

FIGURE 3: Solidification curves with the chosen solid fraction range and the respective temperature variations.

amining the chemical composition of the alloy, it can be observed that high concentrations of silicon, magnesium, and manganese could play a key role in influencing the behavior of the two materials.

Previous studies on Al-Mg-Si alloy systems (Eskin, Suyitno and Katgerman, 2004; Easton, et al., 2012) have experimentally demonstrated that the susceptibility to hot tearing reaches a maximum at approximately 0.25 wt% silicon and around 0.2 wt% magnesium. Additionally, research conducted by Sweet's group (Sweet, Taylor, Easton, Couper and Parson, 2012) indicates that increasing the magnesium content to nearly 1 wt% almost completely mitigates the issue of hot cracking. In contrast, Clyne and Davies (Clyne and Davies, 1975) analyzed the effect of magnesi-

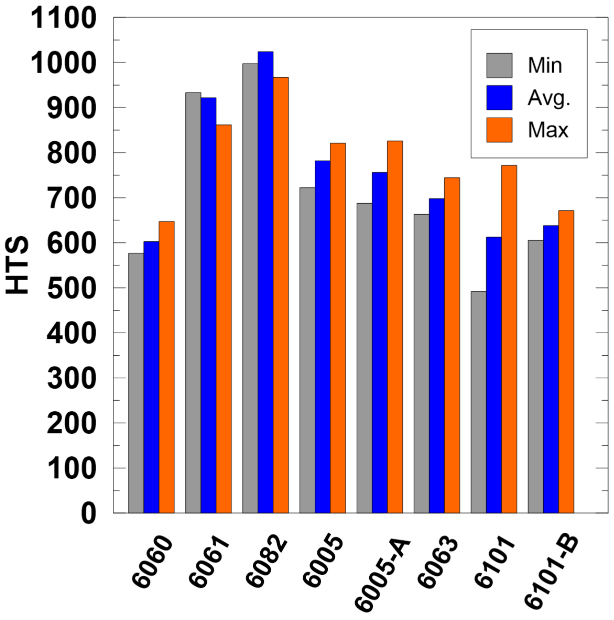

FIGURE 4: Kou's HTS index for minimum, average and maximum chemical composition.

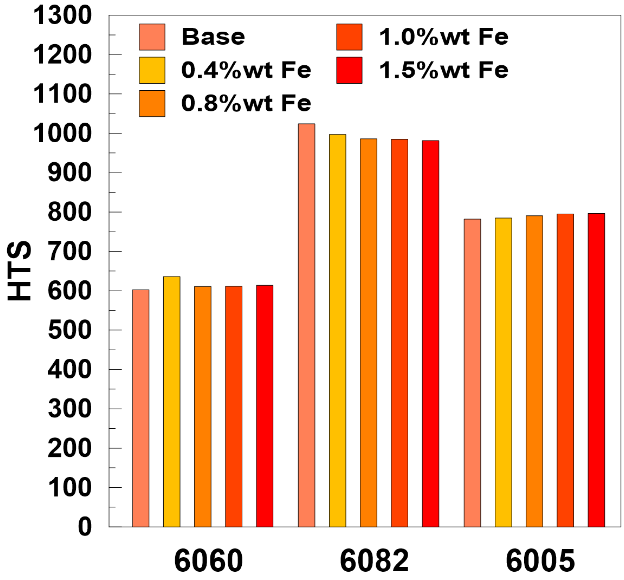

FIGURE 5: Change in cracking indices with varying iron content.

um in aluminum alloys and observed that concentrations close to 1 wt% increase the susceptibility to hot tearing, consistent with observations for 6082 alloys with magnesium concentrations around 0.8 wt%. Li et al. (Li, et al., 2020) found that in magnesium-rich alloys without silicon, hot tearing susceptibility increases, while the addition of silicon appears to prevent the onset of cracking. All these studies agree that increasing the eutectic content of Al + Mg2Si + Si tends to reduce hot tearing susceptibility.

Moreover, Kou (Kou, 2015) compared the vulnerability of A206 and A356 alloys to hot tearing and reported that the A206 alloy, with low silicon content (0.04%) and higher manganese content, suffers more from hot tearing.

The discrepancies between our results and the experimental data reported in the literature may be attributed to the range of solid fractions selected for calculating the Kou index, as there is no precise guideline for choosing this interval.

By inputting all the simulation data for industrial alloys into the statistical software, the following equation was derived through regression analysis:

$$HTS=437-1216*Si-1345*Fe+3858*Mn+1108*Mg+2366*Si^2-13367*Fe^2+3288*Mn^2+3946*Mg^2+19218-SiFe-9782*SiMg-20893*FeMn \quad (2)$$

The model was obtained after removing all non-significant interactions (α>0.1) from the analysis. Notably, the equation exhibits an R-squared value of 99.36%, despite having large residuals. Nevertheless, this equation enables the immediate qualitative assessment of the impact of increasing the content of an element on the hot tearing index without the need for further simulations.

Interesting results emerge from the examination of the Kou indices calculated for alloys with incremental iron content: the histogram in Figure 5 reveals that all three alloys show no changes of the hot crackability index by increasing the iron concentration.

This trend is associated to the solidification curves (Figure 6) calculated for different iron contents: the curves differ exclusively in the initial solidification stage, while they are overlapped in the final phase, especially in the solid fractions range considered for the calculation of the Kou index (0.87-0.94%).

This results seems to be confirmed by Sweet et al. (Sweet, et al., 2013) and Benoit et al. (Benoit, et al., 2023) who argued that the susceptibility to hot tearing is correlated to the iron content, reaching the maximum when the iron content is less than 0.15%. Moreover, the studies also reported that exceeding 0.22% of iron causes an increase of the intermetallic phase, the so-called β-Al5FeSi, favoring the interconnection of the grain boundaries and the eutectic feeding the mushy-zone.

4. CONCLUSIONS

This study aimed to analyze the susceptibility of recycled 6XXX series alloys, with a particular focus on the influence of chemical composition and iron content. The main conclusion drawn from the thermodynamic analysis are as follows:

1. Both 6061 and 6082 alloys exhibit the highest susceptibility to hot cracking, regardless of variations in chemical composition.
2. The higher the levels of magnesium, the greater the hot tearing susceptibility.
3. The reduction in alloying elements content leads to a decrease in hot tearing susceptibility compared to alloys with an average commercial chemical composition.
4. Iron does not significantly influence the hot tearing tendency of 6XXX series alloys. This suggests favorable prospects for scrap handling and recycling in alloy production processes.

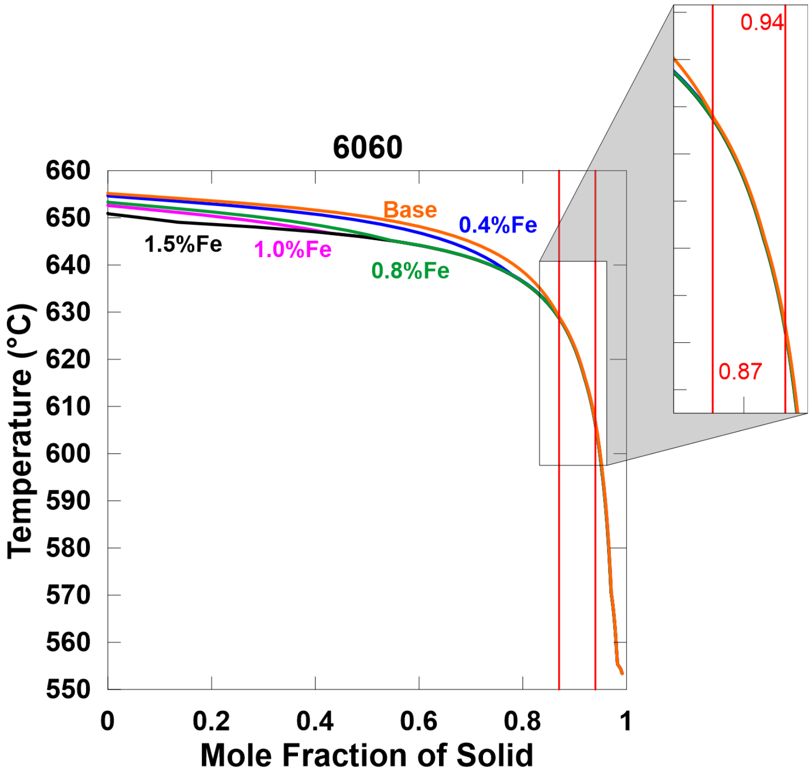

FIGURE 6: Solidification curves with varying Fe content. The overlap of the curves is highlighted.

ACKNOWLEDGEMENTS

This study was carried out within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

REFERENCES

Benoit, M., Whitney, M., Zhu, S., Zhang, D., Field, M., and Easton, M. (2023). The beneficial effect of minor iron additions on the crack susceptibility of rapidly solidified aluminum alloy 6060 toward additive manufacturing applications . Materials Characterization.

Campbell, J. (2015). Complete Casting Handbook. Elsevier Ltd.

Clyne, T., and Davies, G. (1975). A Quantitative Solidification Test for Casting and an Evaluation of Cracking in Aluminium-Magnesium Alloys. The British Foundrymen, 238-244.

Cui, J., and Roven, H. (2010). Recycling of automotive aluminum. Transactions of nonferrous metals society of China, 2057-2063.

D'Errico, F., and Mattavelli, D. (2017). Secondary Aluminum Alloys Processed by Semisolid Process for Automotive Application. The Minerals, Metals and Materials Society.

Easton, M., St. John, D., and Sweet, L. (2010). Grain Refinement and Hot Tearing of Aluminium Alloys - How to Optimise and Minimise . Materials Science Forum, 630, 213-221.

Easton, M., Wang, H., Grandfield, J., Davidson, C., Stjohn, D., Sweet, L., and Couper, M. (2012). Observation and prediction of the hot tear susceptibility of ternary Al-Si-Mg Alloys. Metallurgical and Materials Transactions A, 3227-3238.

Eskin, D., Suyitno, and Katgerman, L. (2004). Mechanical properties in the semi-solid state and hot tearing of aluminium alloys. Progress in Materials Science.

Feurer, U. (1977). Quality control of engineering alloys and the role of metals science. Delft.

Graf, A. (2021). Aluminum alloys for lightweight automotive structures. In Materials, Design and Manufacturing for Lightweight Vehicles (pp. 97-123). Elsevier Ltd.

Hu, B., Li, D., Li, Z., Xu, J., Wang, X., and Zeng, X. (2021). Hot Tearing Behavior in Double Ternary Eutectic Alloy System: Al-Mg-Si Alloys. Metallurgical and materials transactions a.

Kou, S. (2015). A criterion for cracking during solidification. Acta Materialia, 88, 366-374.

Li, R., Wang, M., Li, Z., Cao, P., Yuan, T., and Zhu, H. (2020). Developing a high-strenght Al-Mg-Si-Sc-Zr alloy for selective laser melting: crack-inhibiting and multiple strenghtening mechanism. Acta Materialia, 83-98.

Li, S., and Apelian, D. (2011). Hot tearing of aluminum alloys a critical literature review. International Journal of Metalcasting.

Möller, H., Daswa, P., and Govender, G. (2015). The mechanical properties of rheo-high pressure die cast Al-Mg-Si-(Cu) 6XXX series alloys. Solid State Phenomena, 61-66.

Niyama, E. (1977). Japan-Us joint seminaron solidification of metals and alloys. Japan society for promotion of science.

Padamata, S. K., Yasinskiy, A., and Polyakov, P. (2021). A Review of Secondary Aluminum Production and Its Byproducts. JOM, 73(9), 2603-2614.

Rappaz, M., Drezet, J.-M., and Gremaud, M. (1999). A new hot tearing criterion. Materials Transactions, 449-455.

Sweet, L., Easton, M., Taylor, J., Grandfield, J., Davidson, C., Lu, L., . . . Stjohn, D. (2013). Hot Tear Susceptibility of Al-Mg-Si-Fe Alloys with Varying Iron Contents. Metallurgical and materials transactions a.

Sweet, L., Taylor, J., Easton, M., Couper , M., and Parson, N. (2012). Chemical additions to reduce hot tearing in the cast house. Light Metals 2012 - TMS (the minerals, Metals and Materials Society) 2012.

Van den Eynde, S., Bracquené, E., Diaz-Romero, D., Zaplana, I., Engelen, B., Duflou, J., and Peeters, J. (2022). Forecasting global aluminium flows to demonstrate the need for improved sorting and recycling methods . Waste Management, 231-240.