# INFLUENCE OF CHEMICAL COMPOSITION ON THE HOT TEARING SUSCEPTIBILITY OF WROUGHT 6005 ALUMINUM ALLOYS

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**Abstract**

Hot tearing is one of the most critical casting defects that affect the castability of an alloy and the final integrity of a component. Despite being extensively studied over the past 70 years, multiple theories persist regarding the mechanism that control the crack development and the key influencing phenomena. Most of the theories concur that the susceptibility is influenced by factors such as the chemical composition of the alloy, the cooling rate, and the microstructure of the alloy. This work aims to investigate the hot tearing susceptibility of wrought Al alloys. Using the Kou criterion based on thermodynamic calculations, the influence of different levels of alloying elements and impurities, such as Mg, Si, Fe, and Mn on the alloy hot tearing susceptibility has been investigated.

Thermodynamic simulation results have shown that variations in the chemical composition of the alloy lead to discrete changes in the hot tearing susceptibility index. Furthermore, the obtained results emphasized the critical role of selecting the solid fraction range, identified as the most vulnerable region for hot cracking formation. This selection proves key role in obtaining results that are reflected in industrial practices. These findings offer insight into the castability of wrought alloys and present a method for optimizing industrial process design.

**Keywords:** Hot tearing, thermodynamic simulation, foundry, aluminum wrought alloys

## 1. INTRODUCTION

In recent decades, partly due to the efforts of European legislators, the use of aluminum components in automotive manufacturing has significantly increased [1]. However, to further promote their application, it is essential to develop alloys that provide mechanical properties comparable to those of steel components. This goal is often achieved by adjusting the alloy's chemical composition, as the properties of aluminum alloys are controlled by the intermetallic compounds present in their structure [2]. Among the various families of aluminum alloys, the 6XXX series, which belongs to the Al-Mg-Si system, offers a combination of yield strength and elongation that makes it a leading choice for automotive components [3].

Currently, considering the high energy costs of primary aluminum production and the fact that approximately 75% of the aluminum produced to date is still in use [4], a shift towards using recycled secondary alloys is increasingly necessary [5, 6]. This is even though wrought alloys are highly sensitive to impurity levels resulting from the recycling process.

Furthermore, the 6XXX alloys are susceptible to hot tearing, a casting defect that results in cracks compromising the structural integrity of the component. Hot tearing is a highly complex phenomenon influenced by multiple factors, such as the chemical composition, the cooling rate and the microstructure. Moreover, its causes are not entirely clear, as evidenced by the extensive literature on the subject [7, 8, 9].

### 1.1 Hot tearing prediction

Since the mid-1900s, several theories have been proposed to explain the mechanisms controlling hot tearing, with many of these theories compiled in Eskin's 2004 review [7]. However, many research groups have focused on developing models and predictive criteria to provide qualitative insights into an alloy's tendency to crack during hot tearing. Two of the most acclaimed models are the Clyne-Davies model [10] and the Rappaz-Drezet-Gremaud (RDG) model [8]. The former is based on the characteristics of the liquid phase during the final stages of solidification, with the assumption that feeding can occur when the liquid fraction ranges from 0.6 to 0.1, while a vulnerability zone exists for liquid fraction values between 0.1 and 0.01. The RDG criterion, on the other hand, is a more complex two-phase model that considers pressure drops related to shrinkage and deformations linked to fluid flow. Both models contain parameters that must be derived from experimental tests, and the results do not always align with reality.

Therefore, it is often preferred to obtain qualitative data on hot cracking without laboratory testing. This can be achieved using the Kou criterion [11]. This criterion defines the hot tearing susceptibility (*HTS*) of an alloy through the formula:

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

where $f_S$ represents the solid fraction, and $dT$ is the temperature interval corresponding to the chosen solid fraction range. It is worth to notice that the Kou criterion lacks a precise indication of the solid fraction interval to use but suggests selecting it when the solid fraction approaches 1.

The curve of $T$ vs. $f_S$ of a metallic material, often called the solidification path, can be calculated using thermodynamic calculation software; consequently, the *HTS* index, according to the Kou criterion, can be derived from the steepness of the curve of $T$ vs. $(f_S)^{1/2}$, near $(f_S)^{1/2} = 1$ [11].

As the chemical composition is one of the main factors influencing the solidification path of an alloy, it can be useful to predict the hot cracking susceptibility of different alloys under the same solidification conditions. As reported in literature for binary alloys [12, 13] and for more complex systems[14], the tendency to hot tearing varies with chemical composition following a relationship known as the lambda ($\Lambda$) curve.

In the present work, the Kou criterion was applied to evaluate how the levels of alloying elements (Si ad Mg) and the impurities (Fe and Mn, raising from end-of-life scrap remelting processes) can impact on hot tearing susceptibility of wrought 6xxx alloys and how the choice of solid fraction interval can modify the response of the index.

## 2. MATERIALS AND METHODS

To evaluate the impact of chemical composition on hot tearing susceptibility a full factorial design of experiment (DOE) was designed, varying the content of Fe, Mn, Mg, and Si across four levels, as reported in **Table 1**. The compositional ranges were selected to provide valuable data for the entire 6XXX alloy family and the elements were varied in steps of 0.2 wt%.

**Table 1** Design of experiment (DOE) outlining the variation of Fe, Mn, Mg and Si content (in wt%)

| Si | Fe | Mn | Mg |
|---|---|---|---|
| 0.6 | 0.2 | 0.0 | 0.4 |
| 0.8 | 0.4 | 0.2 | 0.6 |
| 1.0 | 0.6 | 0.4 | 0.8 |
| 1.2 | 0.8 | 0.6 | 1.0 |

A total of 256 alloys with different chemical compositions were obtained from the DOE and thermodynamic calculations were conducted using the Thermo-Calc software with Al-based alloy database (TCAL7, version 7.1). For all the alloys, the simulation parameters were an initial temperature of 750 °C and a computational step size of 1 °C.

Solid fraction-temperature curves were derived by setting the solidification under non-equilibrium conditions, utilizing the Scheil-Gulliver equation. **Figure 1** presents a simulation output of a common 6xxx alloy, which includes the solidification path of the alloy and the phases formed during the solidification process.

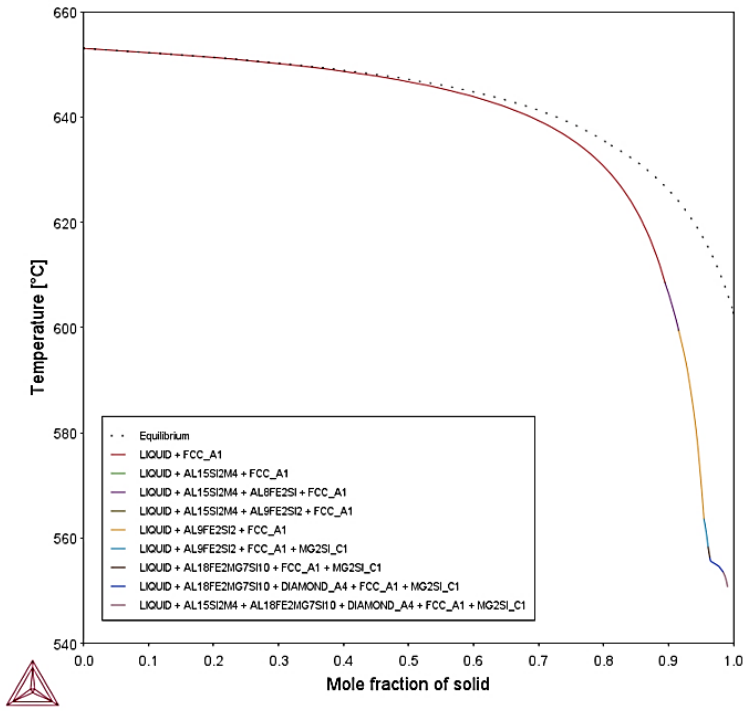



**Figure 1** Scheil solidification path of 6005 alloy calculated by Thermo-Calc software

Using the data from the thermodynamic simulations, the Kou index was calculated for each alloy in three different ranges of solid fraction to evaluate their impact of the hot tearing susceptibility. The three solid fraction intervals considered in this study were: i) 0.77÷0.83, ii) 0.87÷0.94 and iii) 0.92÷0.98.

The first interval was chosen around the dendritic coherency point [7, 15]; the second range matches the one selected by Kou [11]; lastly, the third interval aligns with the *vulnerable region* according to the Clyne-Davies theory[10].

Statistical analysis of the simulation data was performed using Minitab software. The analysis was refined by excluding all parameters that were non-significant to the variation of the index (p-value > 0.1). The effect of individual elements on the susceptibility index was analyzed using a factorial plot.

## 3. RESULTS AND DISCUSSION

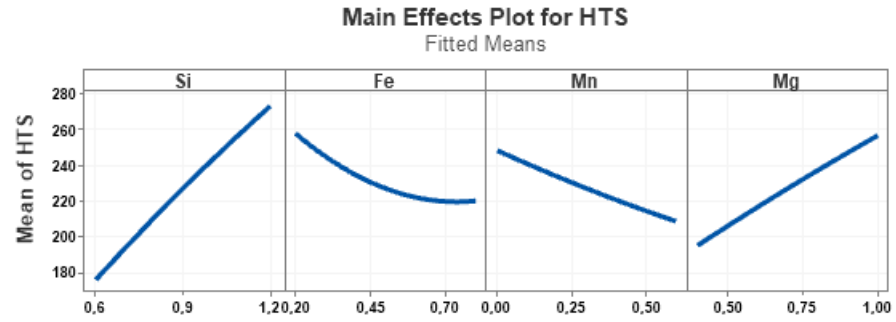
Considering the *HTS* index values calculated in the first solid fraction range (0.77÷0.83), the alloy with the lowest susceptibility to hot tearing contains (in wt%) 0.6 % Si, 0.8 % Fe, 0.6 % Mn, and 0.4 % Mg. In contrast, the alloy with 1.2 % Si, 0.2 % Fe, 0 % Mn, and 1 % Mg exhibits the highest susceptibility to hot tearing, with an index value 245% higher than the former.

From the impact of individual elements on the *HTS* index in **Figure 2(a)**, it can be observed that increasing silicon and magnesium content in the alloy correlates with an increase in the index value. Specifically,

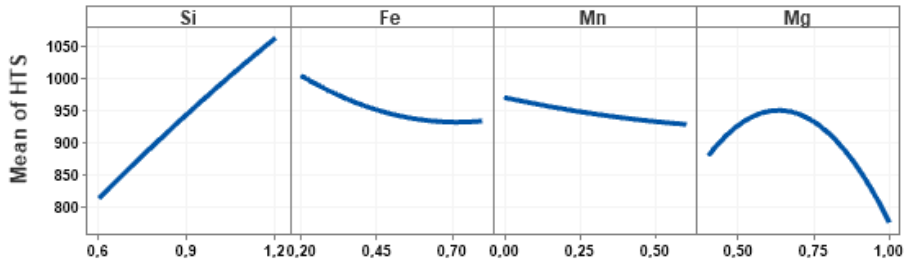
enhancing the Si content from 0.6 wt% to 1.2 wt% results in a 55% rise in the index, while increasing magnesium from 0.4 wt% to 1 wt% results in a 37% increase. Conversely, iron and manganese appear to have a beneficial effect on hot tearing resistance, leading to a slight reduction in the index value when their quantities increase from the minimum to the maximum levels considered in this work.

In the 0.87÷0.94 range, the chemical compositions of the best and worst-performing alloys generally coincide with those of the previous range. However, the influence of the alloying elements changes slightly - see **Figure 2(b)**. The slopes of the curves related to the iron and manganese content decrease, while magnesium exhibits the so-called *Λ*-shaped curve. The fact that this trend is observed only for magnesium, is attributed to the concentration ranges considered for the individual elements, which may truncate the curve. For silicon, it is noted that we are before the cusp point, while for iron and manganese, the inversion point is either surpassed or not detected due to the composition increments fixed at 0.2 wt%, thereby losing any potential information between levels. Literature indicates that manganese exacerbates hot tearing for levels below 0.1 wt% [16], while Clyne and Davies [10] in their study on Al-Mg systems found maximum susceptibility at around 1 wt% Mg. This finding contrasts with the study by Sweet et al. [17], which shows that magnesium levels around 1 wt% can eliminate crack formation in 6060, 6061, and 6005A alloys. Sweet also confirms in another article [18] that the highest susceptibility to hot tearing occurs for iron levels between 0.05 and 0.15 wt%, whereas higher iron content improves the alloy, reaching a nearly flat trend for levels above 0.25 wt%.

(a)




(b)




(c)

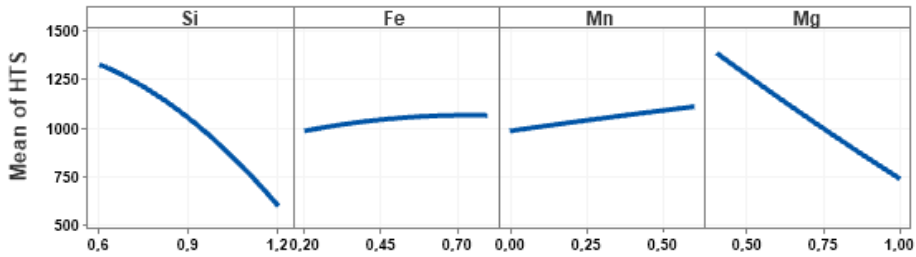



**Figure 2** Effect of Si, Fe, Mn and Mg on the hot tearing susceptibility (*HTS*) in the three solid fraction intervals. (a) 0.77÷0.83; (b) 0.87÷0.94; (c) 0.92÷0.98

The most intriguing result emerges from the analysis of the data collected in the third solid fraction interval ($f_S$ = 0.92÷0.98). In this range, the alloy containing 1.2 wt% Si, 0.6 wt% Fe, 0.4 wt% Mn, and 1 wt% Mg is the

least prone to hot tearing, while the alloy with the highest susceptibility exhibits the same chemical composition as the best-performing alloy in the 0.77÷0.83 range (lowest levels of Si and Mg).

As can be deduced by comparing the effect of Si and Mg on the *HTS* index for the two intervals - **Figures 2(a)** and **2(c)**, it is evident that the correct selection of the solid fraction range is a key factor for the calculation of *HTS* index according to Kou criterion, since it can lead to diametrically opposite results.

The opposite effects of Si and Mg on *HTS* in the two solid fractions ranges can be attributed to the different steepness values in the solidification curves of alloys with different chemistry.

In fact, from the simulated solidification curves (here not reported) it appears that, in the first interval of solid fraction, the alloys with the lowest content of alloying elements have a lower steepness than the alloys with higher content while, in the third interval, their steepness becomes higher.

It is worth to mention the solidification curves are governed by the thermodynamics of the alloy and the kinetics of the reactions occurring during cooling. In industrial processes, the solidification of a component occurs under defined "non-equilibrium" conditions due to the high cooling rates generated. Additionally, the solidification path of an alloy is influenced by the phenomenon of micro-segregation, which refers to the non-uniform distribution of alloying elements in the liquid phase during the solidification process.

The distribution of elements in the various phases is controlled by the partition coefficient *K* [19, 20], defined by the equation:

$$K = C_S/C_L \quad (2)$$

where $C_S$ represents the concentration of solute atoms in the solid phase and $C_L$ the concentration in the liquid phase, both derived at the solid-liquid interface. The partition coefficient thus helps quantify the inhomogeneity of the solidification process and allows for more accurate predictions of the phase fractions formed under non-equilibrium conditions [21]. Current thermodynamic simulation tools, such as ThermoCalc, utilize the CALPHAD [22] calculation method and reference the Scheil equation [23]. The latter defines the composition of the solid during solidification according to the equation:

$$C_S = K\, C_0\, (1 - f_S)^{(1-K)} \quad (3)$$

derived under the assumptions of no solute diffusion in the solid phase and complete solute miscibility in the liquid phase. From this equation (3), it can be observed how the partition coefficient *K* plays a fundamental role in describing the cooling behaviour of an alloy and, notably, the *T* vs. $f_S$ curve obtainable from the simulation.

Furthermore, this leaves the assessment of the chemical composition's impact on hot tearing susceptibility open-ended. It can only be stated that Si and Mg consistently exhibit the most significant influence on the index value in all three cases, while Fe and Mn have a minor effect. Since the Kou index provides a qualitative measure of an alloy's resistance to hot tearing, small index variations do not definitively indicate which alloy performs better during casting.

## 4. CONCLUSION

This study aimed to evaluate the impact of chemical composition on the hot tearing resistance of the 6XXX alloy family, with a particular focus on the content of Si, Fe, Mn, and Mg. Additionally, the study assessed how the results of Kou's predictive index vary with different solid fraction intervals. The main findings can be summarized as follows:

- Magnesium and silicon are the elements with the most significant impact on hot tearing resistance.
- Iron and manganese appear to have a reduced effect on the susceptibility index, potentially opening new avenues for the use of secondary alloys.

- The Kou index provides inconsistent and even contradictory results depending on the solid fraction interval considered, indicating the need for refining the index.

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