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Full Length Article

# Influence of alloying elements on hot tearing susceptibility of Mg–Zn alloys based on thermodynamic calculation and experimental

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**Abstract**

Based on the hot tearing index $|\Delta T/\Delta(f_s)^{0.5}|$ recently proposed by Kou and the thermodynamic calculations of Pandat software, Al, Cu, and Mn elements were picked up and their influence on hot tearing susceptibility of Mg–$x$Zn (x = 6, 8, 10, wt%) alloys was studied by experiments. The results indicate that Al addition can significantly reduce the hot tearing susceptibility of Mg–Zn alloys. Either 0.5Cu or 0.3Mn addition individually can reduce the HTS of the Mg–6Zn–(1, 4) Al alloys, while adding together increases the susceptibility. The addition of 0.5Cu and 0.3Mn both individually and together increases the HTS of Mg–8/10Zn–1Al alloys. Based on the experimental and calculation results, the index can be modified to $|\Delta T/\Delta(f_s)^{0.5}|(d)^2$ for more accurate prediction on the hot tearing resistance of Mg–Zn based alloys. Grain refinement significantly improves the hot tearing resistance of Mg–Zn based alloys.


*Keywords:* Hot tearing susceptibility; Mg–Zn; Alloying element; Thermodynamic calculation; Grain size.

## 1. Introduction

As one of the lightest structural materials, with their high specific strength and low density, magnesium (Mg) alloys are one of the most promising materials for lightweight applications. As most Mg alloys are initially prepared by casting processes, casting abilities are quite important for their actual applications. Unfortunately, Mg alloys are susceptible to cracking during solidification, which is one of the most fatal defects, namely, hot tearing or hot cracking. Previous studies demonstrate that hot tearing arises above the solidus temperature as a result of obstructed contraction during solidification, regularly in the region of mushy zone, where the liquid is not sufficient to fill the cavities, especially at a sharp change of cross section [1].

Considering the fact that the traditional trial-and-error method is time-consuming and laborious, a suitable computational model to predict the hot tearing susceptibility (HTS) of Mg alloys can help exclude alloy compositions that have poor hot tearing resistance during alloy design. Over decades, several models and criteria were presented for hot tearing. These criteria includes those based on nonmechanical aspects, such as Feurer [2], Clyne-Davies [3], and Katgerman [4], those based on mechanical aspects, such as Prokhorov et al. [5], and those that combined these two features, such as the Rappaz–Drezet–Gremaud (RDG) model [6]. However, none of these existing criteria is very qualitatively consistent with the casting practice because of the complex mechanisms acting

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during the solidification of metals. Recently, Kou [7] proposed that tearing initiates at preexisting nucleation sites and propagates if the difference of separation rate of two neighboring grains due to tensile deformation and their growth rate toward each other exceeds the liquid feeding rate along the grain boundary. An index for the hot tearing tendency of an alloy during solidification was also put forward, that is, $|dT/d(f_s)^{0.5}|$ near $(f_s)^{0.5}=1$, where $T$ is temperature and $f_s$ is the fraction of solid. Based on this index and thermodynamic software Pandat, Kou calculated the hot tearing tendencies of some aluminum alloys and compared the results with the practical HTS experimental data in casting practice. As a result, the calculations were in fairly accordance with the experimental values. Therefore, $|dT/d(f_s)^{0.5}|$ near $(f_s)^{0.5}=1$ seems to be a good criterion for the prediction of HTS of an alloy.

Hot tearing resistances of Mg–Al [8], Mg–Zn [9], Mg–Gd [10], and Mg–Zn–Y [11] alloys have been studied. Zn addition to Mg alloy could improve the strength and hardness as well as the corrosion resistance [12]. Mg–Zn based alloys have excellent mechanical properties, including both strength and ductility, along with low cost. However, they have a wide freezing range and are prone to hot tearing during casting. Therefore, if the hot tearing resistance of Mg–Zn based alloys could be improved, they will have wide applications.

In the present study, the hot tearing index $|\Delta T/\Delta(f_s)^{0.5}|$ recently proposed by Kou [7] is used to select alloying elements in order to reduce the hot tearing susceptibility (HTS) of Mg–Zn based alloys. Al, Cu, and Mn elements are picked up and their influence on hot tearing susceptibility of Mg–$x$Zn ($x=6$, 8, 10, wt%) alloys was determined by constrained rod casting.

## 2. Prediction method and selection of alloying elements

### 2.1. Prediction of HTS based on the index $|dT/d(f_s)^{0.5}|$

Hot tearing index $|dT/d(f_s)^{0.5}|$ based on the criterion proposed by Kou [7] indicates that a higher value of $|dT/d(f_s)^{0.5}|$ near $(f_s)^{0.5}=1$ means a higher hot tearing susceptibility. The index can be seen from the steepness of the $T$ and $(f_s)^{0.5}$ curve near $(f_s)^{0.5}=1$, which can be calculated using commercial thermodynamic software Pandat and alloy database. Kou [7] confirmed that the approximation of index $|\Delta T/\Delta(f_s)^{0.5}|$ in the range of $0.87<f_s<0.94$ agreed with some experimental data in Al casting alloys. The validity of the index to predict the hot tearing susceptibility of Mg casting alloys will be assessed in the present study.

The effect of Zn content on the susceptibility of binary Mg–Zn alloys is discussed first as follows: in order to see whether the proposed index of $|dT/d(f_s)^{0.5}|$ near $(f_s)^{0.5}=1$ can produce a λ-shaped curve and a peak susceptibility around 1.5% Zn (hereafter, all compositions are in weight percent unless otherwise stated) reported in several experimental studies, e.g. Le Zhou et al. [9]. Based on Mg database and Pandat software, the curve of $T$ vs. $f_s$ of Mg–Zn based alloys during solidification was determined. The curves of $T$ vs. $(f_s)^{0.5}$ for binary Mg–Zn alloys are shown in Fig. 1a. An average steepness $|\Delta T/\Delta(f_s)^{0.5}|$ with $0.9<f_s<0.99$ (corresponding to $0.949<(f_s)^{0.5}<9.995$ and thus $\Delta(f_s)^{0.5}=0.0463$, about in the region of mushy zone) is used as an approximation. The plot of $|\Delta T/\Delta(f_s)^{0.5}|$ vs. $(f_s)^{0.5}=1$ yields a λ-shaped curve with the peak around 1.5 wt% Zn (Fig. 1b), which agrees well with the experimental data of Zhou et al. [9].

Fig. 2 shows the calculation results of the predicted susceptibility of four series alloys, whose hot tearing susceptibilities were tested in experiments [13–16]. Fig. 2a indicates that with the increase of Zn addition to Mg–9Al alloy, the predicted values of the HTS based on the index increase, which is in agreement with the experimental results demonstrated by Wang et al. [13]. The effect of Al addition to Mg–1.5Zn alloy on the susceptibility was calculated and shown in Fig. 2b, predicting that Al addition reduces the HTS of Mg–1.5Zn alloy. The prediction is consistent with the recommendation that Al addition can increase the hot tearing resistance of Mg–1.5Zn alloy, as proposed by Zhou et al. [14]. Fig. 2c demonstrates a λ-shaped curve with the peak around 0.5 wt% Cu, consistent with Wang's results [15], which indicates that 0.5 wt% Cu addition can reduce the HTS of Mg–6Zn alloy. Furthermore, Zheng et al. [16] investigated the susceptibility of Mg–2.5Zn–$x$Y–0.5Zr alloys, and the experimental results of HTS are as follows: $MgZn_{2.5}Y_2Zr_{0.5} > MgZn_{2.5}Y_{0.5}Zr_{0.5} > MgZn_{2.5}Y_4Zr_{0.5} > MgZn_{2.5}Y_6Zr_{0.5}$, consistent with the predicted tendency using the index in Fig. 2d.

Therefore, the predictions based on the index $|\Delta T/\Delta(f_s)^{0.5}|$ are consistent with the hot tearing results of Mg–9Al–$x$Zn [13], Mg–1.5Zn–$x$Al [14], Mg–6Zn–$x$Cu [15] and Mg–2.5Zn–$x$Y–0.5Zr [16] alloys. It suggested that the index $|\Delta T/\Delta(f_s)^{0.5}|$ based on thermodynamic software Pandat and Mg database is useful and can be used to study the influence of chemical compositions on the hot tearing resistance of Mg–Zn based alloy.

### 2.2. Selection of alloying elements

Fig. 3 shows the prediction results of hot tearing tendencies of Mg–Zn–Al alloys based on the index and Pandat. The alloys containing 6–10% Zn tend to have relatively lower hot tearing tendencies. Therefore, Mg–$x$Zn ($x=6$, 8, 10, wt%) were chosen as basal alloys. From previous studies, it is observed that Al content addition to Mg–Zn alloy can increase the hot tearing resistance [14,17]. Hence, 1% and 4% Al addition were chosen as alloying elements.

Haoyu and co-workers [18] studied the susceptibility of Mg–Zn–Mn alloys and proposed that suitable amounts of Mn addition to Mg–6.5Zn alloy can reduce the hot tearing susceptibilities. Wang et al. [15] investigated the effect of Cu addition on the hot tearing susceptibility of Mg–6Zn–0.6Zr alloy and the results showed that 0.5% Cu-containing alloy exhibited lower hot tearing tendency. Therefore, in order to improve the hot tearing resistance of Mg–Zn–Al based alloys, 0.5% Cu and 0.3% Mn were selected as alloying elements. Table 1 lists the prediction results of the influence of alloying elements on the hot tearing susceptibility (HTS) of Mg–Zn based alloys. It is shown that the addition of 1% and 4% Al,