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# AZ-Mg Alaşımlarının Katılaşma Çatlama Duyarlılığına Karşı Dolgu Metal ve Alaşım Elamanlarının Etkilerinin Tahmin Edilmesi

Tayfun SOYSAL[1*]

**ÖZET:** Katılaşma çatlağı, magnezyum (Mg) alaşımlarının kaynağı için kaygı verici bir unsurdur. Maksimum $\left| dT/d(f_S)^{1/2} \right|$, bir indeks olarak Pandat termodinamik yazılımı ile alüminyum ve çinkonun başlıca alaşım elementlerinin olduğu AZ-Mg ark kaynaklarının katılaşma çatlama duyarlılığını tahmin etmede kullanılmıştır. Bu indeksle AZ101 magnezyum kaynak telinin ticari olarak temin edilebilir AZ31, AZ61 ve AZ91 Mg alaşımlarının çatlak duyarlılığını azaltmaya etkisi araştırılmıştır. AZ101 Mg kaynak teli, üç alaşımın da katılaşma çatlağının duyarlılığının azaltılmasında etkili bulunmuştur. Alüminyum ve çinkonun AZ-Mg alaşımlarının katılaşma çatlağına olan etkisi çatlak indeksi ve Pandat ile Scheil katılaşma modeli esas alınarak tahmin edilmiştir. İndekse dayalı tahminler AZ-Mg alaşımlarının deneysel çatlak duyarlılığı verileri ile karşılaştırılmış ve hem tahminlerin hem de deneysel verilerin genel trendinin birbiriyle uyumlu olduğu görülmüştür. Tahminler, katılaşma çatlağı için önerilen kriter ışığında açıklanmıştır.

**Anahtar Kelimeler:** katılaşma çatlağı, kaynak edilebilirlik, magnezyum alaşımları, çatlak duyarlılığı tahminleri

# Estimating the Effects of Filler Metal and Alloying Elements for Against Solidification Cracking Susceptibility of AZ-Mg Alloys

**ABSTRACT:** Solidification cracking is a concern for welding magnesium (Mg) alloys. An index, the maximum $\left| dT/d(f_S)^{1/2} \right|$, was used with the thermodynamic software Pandat to make solidification cracking susceptibility predictions for AZ-Mg arc welds which have the main alloying elements of aluminum and zinc in the magnesium matrix. The effect of AZ101 magnesium filler on reducing crack susceptibility of commercially available AZ31, AZ61 and AZ91 Mg alloys was investigated with the crack susceptibility index. The filler metal AZ101 Mg alloy was found effective to reduce the susceptibility of all the three AZ-Mg alloys to solidification cracking. The influence of the amount of aluminum and zinc in the AZ-Mg alloys on the crack susceptibility was predicted using the cracking index and Pandat based on Scheil solidification model. The predictions based on the index were compared to the experimental crack susceptibility data of the AZ-Mg alloys, and it was seen that the general trend of both predictions and the reported data was consistent with each other. The predictions were explained in the light of the criterion proposed for solidification cracking.

**Keywords:** solidification cracking, weldability, magnesium alloys, crack susceptibility predictions

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## INTRODUCTION

Magnesium (Mg) alloys have various applications such as automotive, aerospace and biomedical owing to their desired properties: light weight, castability, machinability and high strength (Friedrich, 2006). Although welding of Mg alloys is typically done to repair castings, the interest in the welding research for Mg alloys to increase the weldability of Mg alloys has increased (Liu, 2010). One of the challenges in welding of Mg alloys is cracking during solidification, called solidification cracking (Kou, 2020). The cracking phenomenon is also observed during casting, and named hot-tearing by casting community (Campbell, 2011). Solidification cracking susceptibility for Mg alloys have been reported by various studies (Adamiec, 2010; Huang et al., 2011; Kierzek and Adamiec, 2011; Liu and Kou, 2020; Liu and Dong, 2006; Sun et al., 2013; Yu et al., 2010; Demir and Durgutlu, 2014). Solid-state welding can be an alternative to have sound welds (Teker et al., 2018) but fusion welding with appropriate filler metals can save cost and be more versatile.

A number of tests and theories have been proposed to study susceptibility of materials to solidification cracking (Soysal and Kou, 2017). A criterion has been proposed to explain solidification cracking (Kou, 2015a). Formation of columnar dendritic grains during solidification was considered in the criterion. As these grains form and grow next to each other during solidification, they try to bond together. However, due to solidification shrinkage, e.g. 4.2 % for Mg (Flemings, 1974), and thermal contractions, these grains are separated from each other by tensile stresses. Furthermore, grain boundary liquid which flows through the channels between these grains help bonding of these grains filling the gaps caused by the stresses. Solidification cracking occurs if the tensile stresses can separate the grains by exceeding both the grain growth and the liquid flow between the grains. Therefore, if the grain growth rate or liquid flow rate is slow for an alloy during solidification, the alloy is susceptible or sensitive to solidification cracking. The growth of the grains has been related to a crack susceptibility index, the maximum $|dT/d(f_S)^{1/2}|$, in which $T$ and $f_S$ are respectively temperature and fraction solid (Kou S, 2015b). The susceptibility index has been coupled with solidification paths calculated by thermodynamic software and used to make crack susceptibility predictions of the materials. The susceptibility index was interpreted in the following way: if the maximum $|dT/d(f_S)^{1/2}|$ of the material is small, the susceptibility or the tendency to cracking during solidification is low. This index was implemented to theoretically determine the crack susceptibility of aluminum alloys (Liu and Kou, 2015; Liu and Kou, 2016; Liu and Kou, 2017; Soysal, 2021a; Soysal and Kou, 2019a; Soysal and Kou, 2020), magnesium alloys (Liu and Kou, 2020), nickel-based alloys (Xia and Kou, 2020), and carbon steels (Soysal, 2021b; Xia and Kou, 2021). The predictions were verified by transverse motion weldability (TMW) test (Soysal and Kou, 2018; Soysal and Kou, 2019b) which was developed as an alternative to most widely used Varestraint test (Savage and Lundin, 1965). The crack susceptibility index was applied using the $T$ vs $f_S$ curves of the materials and assuming that an extensive bridging occurs between the dendritic grains of the materials at $(f_S)^{1/2}$=0.99, and beyond $(f_S)^{1/2}$=0.99 crack susceptibility ends. This assumption comes from the RDG criterion proposed by Rappaz et al. (1999). It could be worth to note that Cylne and Davies (1981) assumed that the extensive bonding occurs between the grains when $(f_S)^{1/2}$ exceeds 0.995. This assumption was also used for some aluminum alloys with the maximum $|dT/d(f_S)^{1/2}|$ and worked well (Soysal and Kou, 2019a; Soysal, 2021a).

As mentioned earlier, the susceptibility index was used to predict the crack susceptibility of the arc welded magnesium welds made without filler metal, and the predictions were consistent with the TMW test results (Liu and Kou, 2020). In this study, the susceptibility index will be used to investigate the filler metal effect and alloying elements' effect on the crack susceptibility of the most commonly used AZ-Mg alloys such as AZ31, AZ61 and AZ91 which have the main alloying elements of aluminum and zinc in the magnesium matrix. Commercially available filler metal AZ101 Mg alloy have been selected for welding and study the filler metal effect which has not been studied before. The calculated results are compared to the experimental data to verify the accuracy of the work.

## MATERIALS AND METHODS

Solidification cracking susceptibility of the AZ-Mg fusion welds were predicted using the maximum $|dT/d(f_S)^{1/2}|$, the susceptibility index for solidification cracking. Crack susceptibility predictions of AZ31, AZ61 and AZ91 Mg alloys were firstly calculated using the nominal chemical compositions of them given on Table 1. Then, these three alloys were presumed to be arc welded with the filler metal made out of AZ101 Mg alloy of which the nominal chemistry is included in Table 1. The welding conditions of arc welding with one pass can be considered for the imagined fusion welding process. The differences in the effect of the heating cycles of the welds on the crack susceptibility were ignored. The welds were considered to be composed of the workpiece and the filler metal with the ratio of 1:4 (20% workpiece and 80% filler metal). Table 2 shows the weld compositions which were calculated using the nominal chemical compositions on Table 1. $T$ vs $(f_S)^{1/2}$curves of AZ31, AZ61, AZ91 and the welds were calculated using Pandat, commercial thermodynamic software, (Pandat 2020) and its databases regarding the chemical compositions on Tables 1 and 2. As the solidification model of the software, Scheil solidification, which assumes no solid diffusion and complete liquid diffusion (Kou S, 2020), was used for the calculations, as Liu and Kou (2020) used for arc welding of the Mg alloys. The maximum $|dT/d(f_S)^{1/2}|$ on the $T$ vs $(f_S)^{1/2}$curves were examined up to $(f_S)^{1/2}$=0.99. In addition, the influence of the alloying elements of aluminum and zinc on the crack susceptibility of the magnesium alloys was predicted. Contour map of the crack susceptibility was plotted using Pandat. For the contour map of AZ-Mg alloys, 121 alloys were considered. It covers the composition changes from 0.5 to 5wt% for both aluminum and zinc.

**Table 1.** Nominal chemical compositions of the materials (wt%)

| | *Al* | *Zn* | *Mg* |
|---|---|---|---|
| **Workpiece** | | | |
| **AZ31** | 3 | 1 | bal. |
| **AZ61** | 6 | 1 | bal. |
| **AZ91** | 9 | 1 | bal. |
| **Filler metal** | | | |
| **AZ101** | 10 | 1 | bal. |

## RESULTS AND DISCUSSION

### Predicting Filler Metal Effect

Although susceptibility of the AZ-Mg alloys was predicted and experimentally studied by Liu and Kou (2020), they were calculated in this study to illustrate the effect of the filler metal AZ101 Mg alloy on reducing the susceptibility to solidification cracking. Calculated $T$ vs $(f_S)^{1/2}$ curves by Pandat for AZ31 Mg alloy with and without the filler metal AZ101 Mg alloy are shown in Figure 1. The maximum $|dT/d(f_S)^{1/2}|$, in other words the maximum steepness, of the curves were determined and given on the lower right corner of the figure. The maximum steepness for AZ31 Mg alloy without filler metal was found as 9776 °C before $(f_S)^{1/2}$ reaches 0.99 (indicated with black tangent line). When the filler metal AZ101 Mg alloy was considered to be used to weld AZ31 Mg alloy, the maximum steepness was found as 2269 °C. As Kou (2015b) pointed out, if the maximum $|dT/d(f_S)^{1/2}|$ is small, the crack susceptibility is low. Therefore, the filler metal AZ101 Mg alloy can be effective to reduce the susceptibility of AZ31 Mg alloy to solidification cracking lowering the maximum steepness from 9776 °C to 2269 °C. This drastic change in the maximum steepness is the result of changes in the chemical compositions, freezing temperature ranges, and the order of phase formations of the welds. The filler metal makes the important part of the solidification curve shallower. A detailed explanation on this is made at the end of this section.

**Table 2.** Chemical compositions of the welds (wt%) calculated based on 20% of the workpiece and 80% of the filler metal compositions.

| Welds | Al | Zn | Mg |
|---|---|---|---|
| **AZ31-AZ101** | 8.6 | 1 | bal. |
| **AZ61-AZ101** | 9.2 | 1 | bal. |
| **AZ91-AZ101** | 9.8 | 1 | bal. |

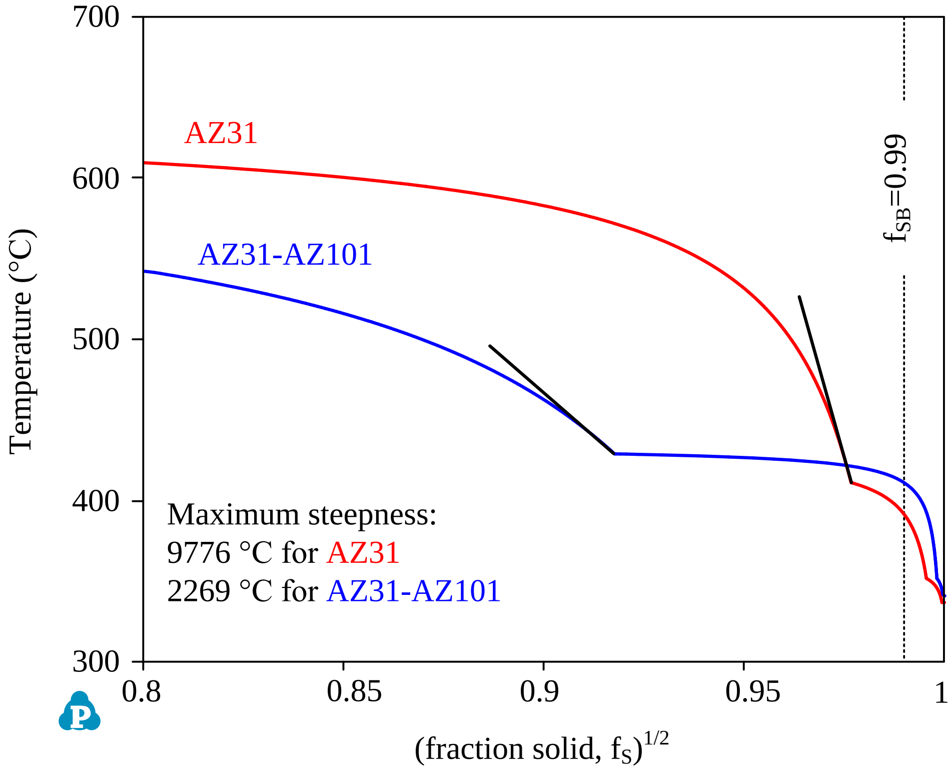


**Figure 1.** *T vs* $(f_S)^{1/2}$curves of AZ31 Mg alloy with and without the filler metal AZ101 Mg alloy

The *T* vs $(f_S)^{1/2}$ curves of AZ61 Mg alloy with and without the filler metal AZ101 Mg alloy are shown in Figure 2. The maximum steepness of AZ61 Mg alloy was found as 3831 °C, and the maximum steepness of the weld metal made with AZ61 Mg alloy and the filler metal AZ101 Mg alloy was found as 2053 °C. The filler metal AZ101 Mg alloy can reduce the crack susceptibility of AZ61 Mg alloy lowering the maximum steepness from 3831 °C to 2053 °C.

Figure 3 shows the *T* vs $(f_S)^{1/2}$ curves of AZ91 Mg alloy with and without the filler metal AZ101 Mg alloy. The maximum steepness of the welds made without and with the filler metal AZ101 Mg alloy were found as 2053 °C and 1768 °C, respectively. Since the maximum steepness of AZ91 Mg alloy decreases using the filler metal AZ101 Mg alloy, the filler metal can be effective to reduce its susceptibility to solidification cracking as well.

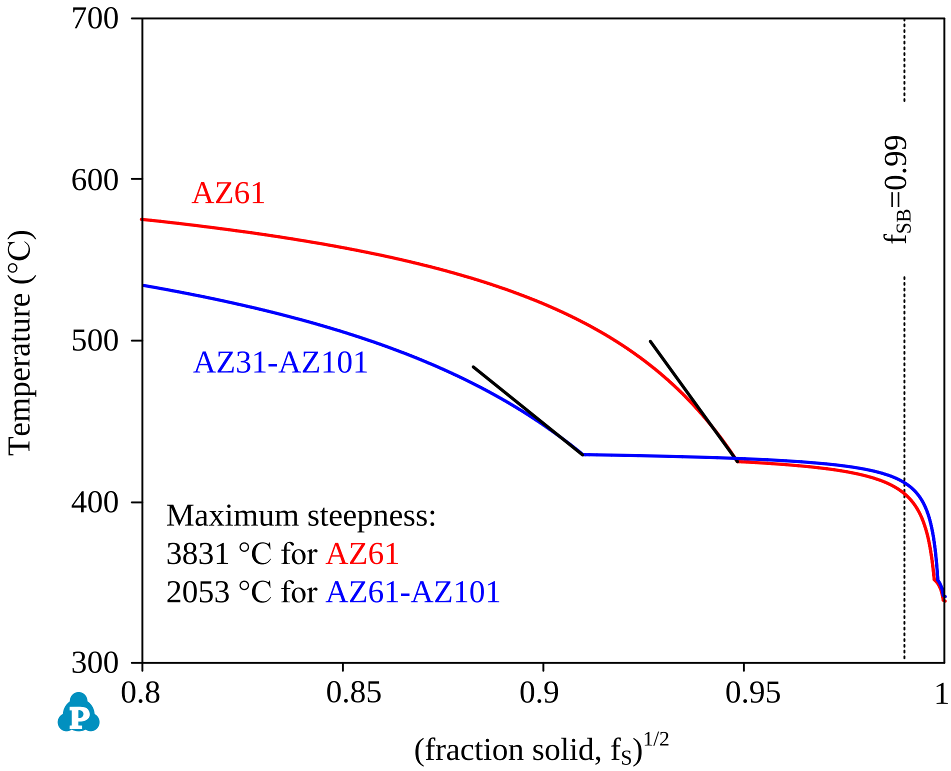


**Figure 2.** *T vs* $(f_S)^{1/2}$ curves of AZ61 Mg alloy with and without the filler metal AZ101 Mg alloy

Solidification cracking susceptibility predictions of all the Mg welds given in Figures 1 to 3 were shown with the bar chart in Figure 4. The bar chart illustrates the maximum $|dT/d(f_S)^{1/2}|$ and indicates that longer the bar, higher the susceptibility to solidification cracking is. The predictions show that the crack susceptibility order of workpiece is AZ31>AZ61>AZ91. Figure 5 shows TMW test results of these three Mg alloys reported by Liu and Kou (2020). The TMW test was conducted by doing a lap welding with gas tungsten arc welding and moving the lower-sheet normal to the welding direction to cause cracking. The magnitude of the moving speed indicates the crack resistance of the weld. As can be seen on the figure, the bar chart for the welds have three regions on the bars: no crack, full crack and transition range (located between no crack and full crack regions). As the moving speed was increased to cause full cracking during testing, some partial crack lengths were seen at some moving speeds. The moving speeds corresponding to these partial cracks are represented by the transition ranges on the figure. If the overall location of the transition range is located at a high moving speed, it means its crack resistance is high. The transition range of the AZ31 Mg alloy is located at a lower level than the other two alloys (the numbers increasing downward on the figure), therefore it has a higher crack susceptibility than AZ61 and AZ91 Mg alloys. The susceptibility order of the three alloys are consistent in both Figures 4 and 5. Since the index cannot be related to any physical property of the welds, the comparison between the predictions and the test results should be made qualitatively. As the predictions on Figure 4 shows, the filler metal AZ101 Mg alloy reduced the crack susceptibility of all the three AZ-Mg alloys. The use of AZ101 Mg alloy as the filler metal helped to reduce the crack susceptibility of both AZ31 and AZ61 Mg alloys significantly but it reduced the crack susceptibility of AZ91 Mg to some extent. Since the susceptibility of AZ91 Mg alloy was not bad compared to the other two alloys, the effectiveness of the filler metal AZ101 Mg alloy on reducing the crack susceptibility is expected to be small.

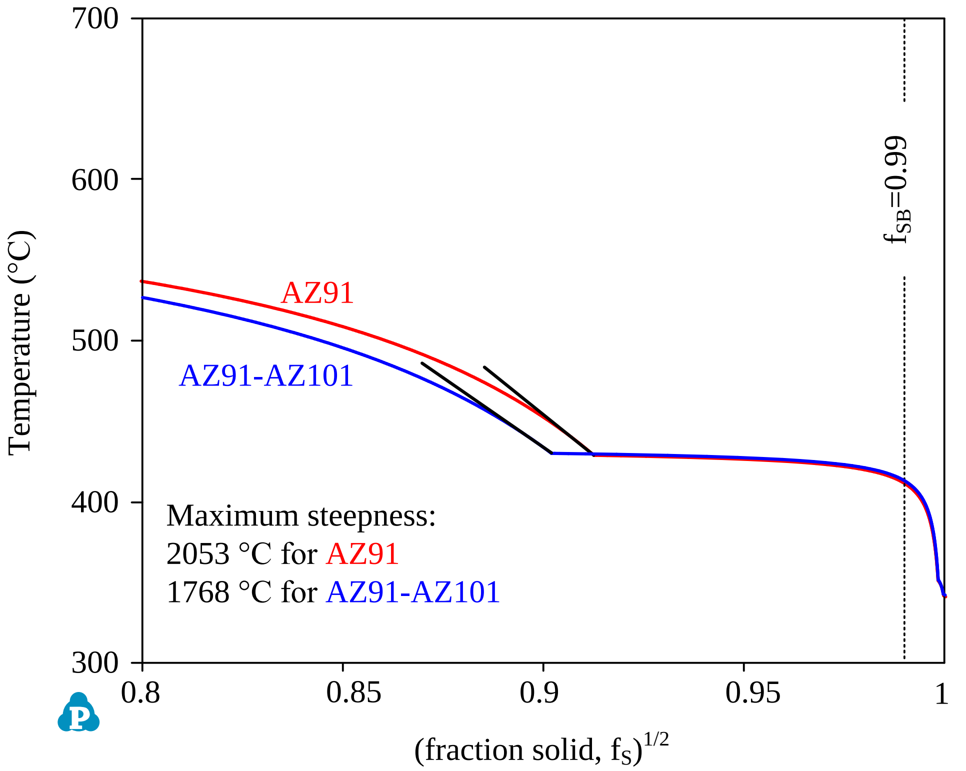


**Figure 3.** *T vs* $(f_S)^{1/2}$ curves of AZ91 Mg alloy with and without the filler metal AZ101 Mg alloy

The crack susceptibility predictions have shown that the filler metal AZ101 Mg alloy can be used for the AZ-Mg alloys to help avoiding solidification cracking. AZ101 Mg alloy contains more aluminum than the other AZ-Mg alloys. Thus, keeping the aluminum content high in the weld metal can help for avoiding solidification cracking. The influence of the alloying elements in the AZ-Mg alloys will be subsequently discussed later. As can be seen from Figures 1 to 3, the filler metal AZ101 lowered the liquidus temperatures and shortened the freezing or solidification temperature ranges of AZ31, AZ61 and AZ91 Mg alloys. This resulted in a fast fraction solid increase as the temperature drops, and hence caused to have shallower *T vs* $(f_S)^{1/2}$ curves. As the fraction solid increases, the growth rate of the grains considered by Kou (2015a) increases during solidification. If the total rate of the grain growth and the liquid flow between the grains exceeds the tensile strain rate during solidification, solidification cracking can be prevented. The filler metal AZ101 Mg alloy helps increasing the growth rate of the dendrites till very end of solidification (corresponding a $(f_S)^{1/2}$ value higher than 0.99), therefore, it is effective to reduce solidification cracking susceptibility of AZ31, AZ61 and AZ91 Mg alloys.

The phases of the AZ-Mg alloys formed during cooling is as follows according to the calculated curves with Scheil solidification model: L → L + HCP → L + HCP + AlMg_Gamma → L + HCP + T_AlMgZn → HCP + T_AlMgZn + MgZn. The black tangent lines shown on the solidification curves in Figures 1-3 which were used to find maximum $|dT/d(f_S)^{1/2}|$ were found at the border of the phase transformation of L + HCP → L + HCP + AlMg_Gamma. When the filler metal AZ101 Mg alloy is used to weld the AZ-Mg alloys, this phase transformation happens faster and the solidification curve becomes shallower. For example, while the aforementioned phase transformation occurs at $(f_S)^{1/2}$ of 0.977 and the temperature of 411°C for AZ31 Mg alloy, it occurs at $(f_S)^{1/2}$ of 0.918 and the temperature of 429°C for AZ31-AZ101 Mg weld. The increased aluminum content of the AZ31-AZ101 Mg weld increases the rate of solidification and hence it results in a shorter freezing time range for cracking to occur. Since faster solidification rates in the welding processes can help for avoiding solidification cracking (Soysal and Kou, 2017; Coniglio and Cross, 2020), the shortened freezing temperature ranges of the welds can be expected to more resistant to solidification cracking.

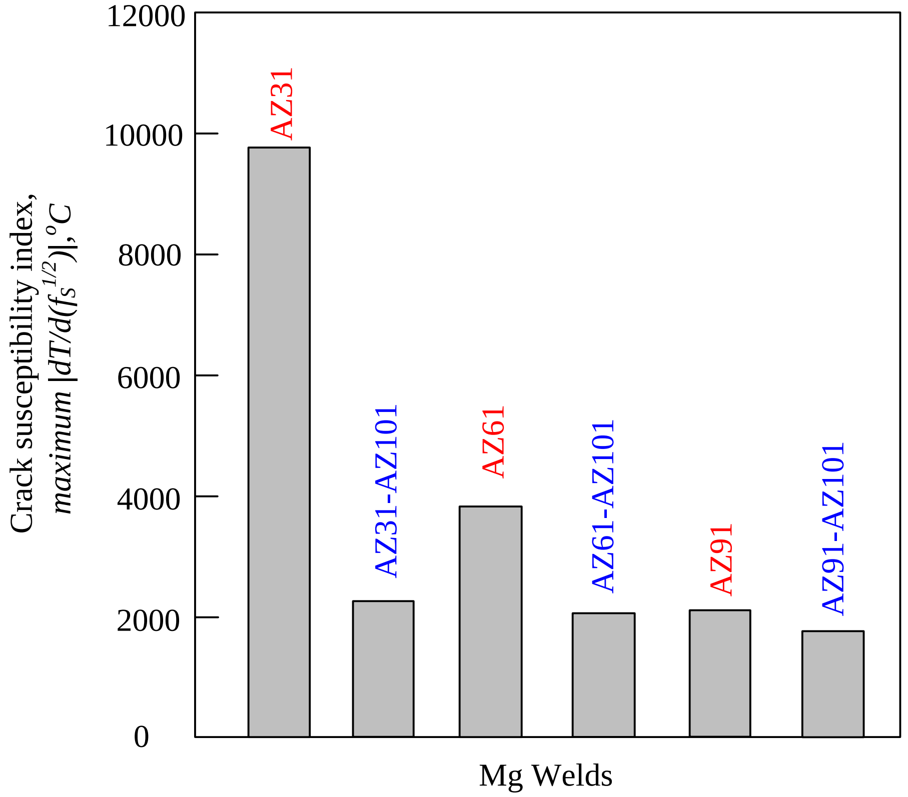


**Figure 4.** Solidification cracking susceptibility predictions of all the Mg welds in Figures 1 to 3 shown with bar chart: longer the bar chart, higher the susceptibility to solidification cracking is.

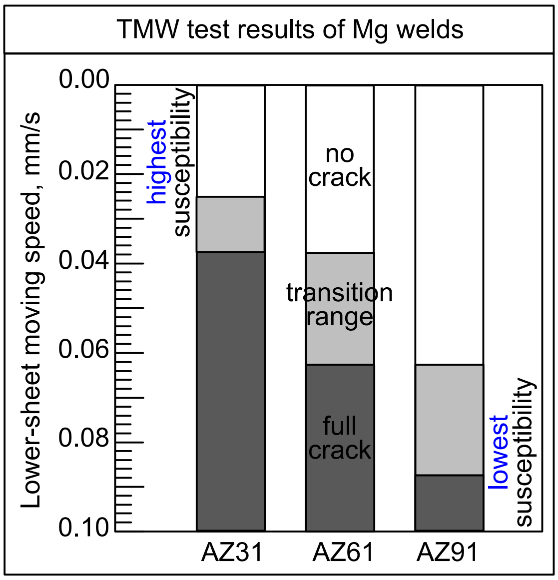


**Figure 5.** Solidification cracking susceptibility test results of AZ31, AZ61 and AZ91 Mg welds obtained by the TMW test (from Liu and Kou, 2020).

**Predicting Effect of Alloying Elements**

The influence of both aluminum and zinc contents was also predicted using Pandat considering 121 alloys which cover the alloying element content ranges of 0.5-5wt% of both aluminum and zinc, and it is shown in Figure 6. According to the figure, the crack susceptibility is very high when the zinc content is around 1.5 wt% with the absence of aluminum which was indicated with red colored region. By increasing the aluminum content in the AZ-Mg alloys the crack susceptibility decreases. It appears that decreasing or increasing the zinc content (going away from the zinc content of 1.5 wt%) also helps for avoiding solidification cracking but increasing aluminum content is more effective in the reduction of the crack susceptibility. If the zinc content is kept constant at 1 wt% just like in the case of the AZ-Mg alloys investigated in this study, the aluminum content of 4 wt% or higher can be helpful to avoid solidification cracking by moving to the purple colored region. As can be seen from the Table 2, the weld compositions have higher aluminum content than 7 wt% so they must fall into the darker purple colored regions, and the chemical compositions of them must be good for avoiding solidification cracking. Furthermore, AZ91 Mg alloy must also fall into the darker purple colored region which indicates low crack susceptibility. In fact, the TMW tests of the AZ-Mg alloys reported by Liu and Kou (2020) shown in Figure 5 has shown that AZ91 Mg alloy has good crack resistance. As mentioned earlier, the increase in the aluminum content of the welds consistently results in the earlier precipitation of AlMg_Gamma phase from liquid and hence the maximum steepness of the solidification curves decreases. On the other hand, increase in the zinc content of the weld (this was observed when the zinc content was increased from 1 wt% to 3 wt%) can result in the delay of the precipitation of AlMg_Gamma phase (phase formation occurs at lower temperatures), and therefore the focused part of the solidification paths can become more steeper. Since steeper solidification paths cause to have a high susceptibility index, the calculated crack susceptibility can increase as the zinc content increases.

Figure 7 shows experimental crack susceptibility data obtained by Zhou (2011) given in the review of Song et al. (2016). The data was obtained using hot tearing susceptibility test setup which was called constrained rod casting test. In this test setup, the geometry of the rods were designed to prevent free solidification shrinkage of the cast alloys to cause cracking during solidification. As can be seen from the figure, there is high crack susceptibility in the red colored region corresponding to the chemical composition of 1.5 wt% zinc content and no or little bit aluminum. It is possible to avoid this high crack susceptible region by adding more aluminum and zinc to the Mg alloys. It seems that increasing aluminum content of the AZ-Mg alloys is more effective in reducing crack susceptibility than increasing the zinc content which is consistent with the predictions demonstrated in Figure 6. The predictions calculated based on Scheil solidification model in Figure 6 were prepared considering arc welding conditions. In arc welding, the solidification time is shorter than that in casting. Longer solidification times promote the solid diffusion during solidification, thus the effect of solid diffusion in arc welding and casting can vary. The crack susceptibility can decrease, and the sensitive compositions can change when solid diffusion is significant in the process (Liu and Kou, 2015). In the predictions given in Figure 6, the effect of solid diffusion on the crack susceptibility is ignored using Scheil solidification model. Because of that, the crack susceptibility may shift in terms of chemical compositions while predicting solidification cracking susceptibility in arc welding compared to the crack susceptibility for casting. Although the high crack susceptible compositions (or crack susceptibility peak) of both Figures 6 and 7 are consistent with each other, there are some differences in how crack susceptibility decreases as the composition changes perhaps due to the differences between the metal processes and amount of solid diffusion in both processes. The predictions can also be made using solidification models which can account for solid diffusion in the selected metal process. However, Scheil solidification model used in the present study is fairly enough for fusion welding of magnesium alloys and can give an idea about the general trend of the crack susceptibility. Both Figures 6 and 7 indicate that increasing aluminum content in the composition of the AZ-Mg alloys can be effective to reduce the crack susceptibility. As for the zinc content, avoiding the rough composition range of 1 to 3 wt% is better for solidification cracking.

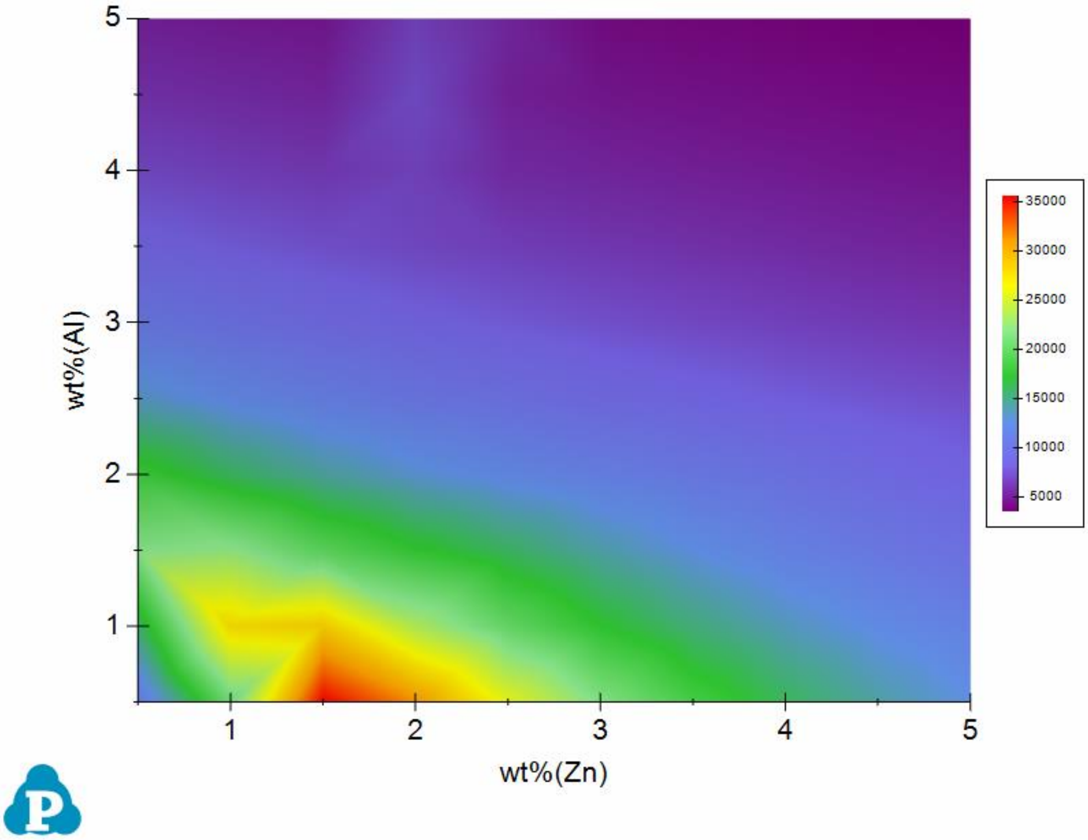


**Figure 6.** Solidification cracking susceptibility predictions of AZ-Mg ternary alloys based on maximum $|dT/d(f_S)^{1/2}|$ calculated by Pandat: crack susceptibility decreases from red colored region to purple colored region.

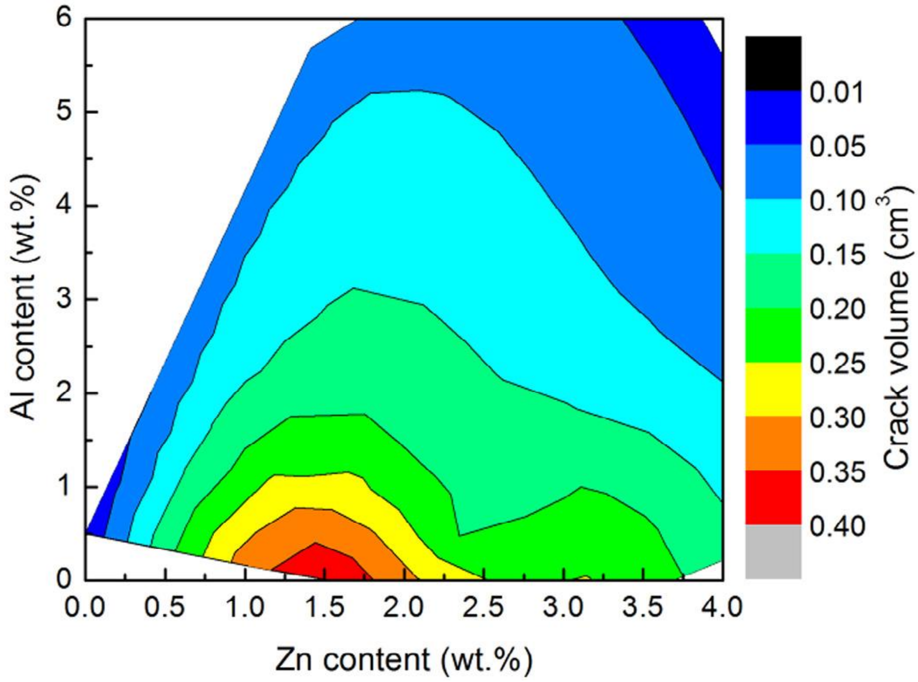


**Figure 7.** Experimental data for hot tearing susceptibility of aluminum-zinc-magnesium ternary alloys from Song et al. (2016).

## CONCLUSION

Crack susceptibility predictions of the AZ-Mg welds with and without filler metal AZ101 Mg were made using the susceptibility index, the maximum $\left| dT/d(f_S)^{1/2} \right|$, which was calculated with the help of commercial thermodynamic software. The filler metal AZ101 Mg alloy was found to be effective in reducing the crack susceptibility of all the three AZ-Mg alloys (AZ31, AZ61 and AZ91 Mg alloys) by lowering their maximum $\left| dT/d(f_S)^{1/2} \right|$. The influence of the amount of the alloying elements (aluminum and zinc) in the AZ-Mg alloys on the crack susceptibility was predicted. The predictions showed that increasing aluminum content of the weld helps for avoiding solidification cracking. The predictions based on the index were compared to literature and verified. The predictions were explained using a criterion proposed for solidification cracking.

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### Conflict of Interest

As an author, I declare that there is no conflict of interest in the planning, execution and writing of the article.

### Author's Contributions

As the author, the planning, execution and writing of the articles was carried out by me.

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