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Short communication

On the ductility potential and assessment of structural quality in Mg alloy castings

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ABSTRACT

Tensile data from literature are reanalyzed to determine ductility potential in magnesium alloys, which has yielded a linear relationship between maximum elongation and yield strength. Ductility potential line is significantly higher than those in the literature. Moreover, grain size, chemical composition, temper do not affect the yield strength-maximum elongation relationship.

1. Introduction

Mg alloy castings have been attractive candidates in load-bearing applications, where weight is critical [1]. The density of Mg alloys ranges from 1.5 g/cm^3 in magnesium–lithium to 1.8 g/cm^3 in magnesium-rare earth alloys [2]. Despite the significant weight savings that can be achieved over other light metals, Mg alloy castings have not been as common in aerospace and automotive applications as aluminum alloys. The barriers to their wider use have been recently addressed [3]: (i) porosity and hot-tearing during solidification, (ii) thermal treatments and (iii) process design to produce high-integrity cast magnesium components with high ductility and strength, low porosity that are free from oxide bifilms. For wider use of Mg alloy castings in structural applications, these barriers need to be removed through careful improvement of casting processes.

Recent research [4] has shown that initial melt quality, handling the molten metal and finally design of the filling system in the mold significantly affect the mechanical properties of castings, including fatigue life [5], elongation (e_F) [6–11] and tensile strength [12–13]. Therefore significant improvement in the quality of magnesium castings should focus on melt preparation and handling as well as filling system design. Such a quality improvement effort requires a metric that can be used to gage the effectiveness of techniques and/or processes implemented. However, there is no such metric available yet for Mg alloy castings. This study is motivated by this gap in the literature.

A metric for the assessment of structural quality of cast Al alloys has been developed [14–17] recently, based on the concept that, when large numbers of data are analyzed together, there is an increased likelihood to come across extreme data points which may reflect the true property potential of the metal. Using this property potential, a quality index that compares actual to potential tensile elongation has been introduced [14–17], along with specific guidelines on where to focus quality improvement efforts, depending on the current quality level. The same approach has been expanded in this study to cast Mg alloys for various compositions. Elongation and yield strength (σ_Y) data from 25 independent studies in the literature have been reexamined to determine the maximum elongation points for a given yield strength level.

2. Background

Mechanical properties in castings are mainly determined by the extent of the structural defects such as bifilms and pores. Bifilms are surface films that are entrained into the liquid metal either through poor handling of the liquid metal or during mold filling if the filling system has not been designed properly [7]. During solidification, bifilms open up under the negative pressure developed in the metal as well as by the diffusion of dissolved gases. They act as heterogeneous nucleation sites for intermetallics

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and pores and/or serve as cracks that lead to hot tearing in the casting. Because of their overwhelming effect on the mechanical behavior, it has been suggested [18] that the microstructure plays almost no role when there are structural defects in castings.

Among all mechanical properties, low ductility is the most prominent symptom of the presence of major structural defects [14]. That is why efforts to increase ductility by changing heat treatment, a practice promoted in traditional metallurgy books as strength-ductility trade-off, has often been fruitless [14,17]. A more effective strategy to increase ductility is to improve the initial melt quality, eliminate liquid metal transfers and design the filling system carefully so that additional oxide bifilms are not entrained [14,19,20].

Strengthening in Mg alloys is achieved in precipitation hardening (e.g., Mg–Zn, Mg–Al and Mg–Ag systems), solute solution hardening and/or grain size hardening following the well-known Hall–Petch equation:

$$\sigma_Y = \sigma_0 + kd^{-0.5} \tag{1}$$

where σ_0 is a material constant (MPa) and d is the grain size (μm). Alloying additions such as Zr and rare earth (RE) elements have been used widely for grain refinement [21] to achieve significant grain size strengthening. Decreasing grain size was also observed to increase ductility [22–23]. The low ductility of cast Mg alloys at room temperature has been attributed [2,24] to cracking along grain boundaries during tensile deformation as a result of only three slip systems being active (in the $<11\bar{2}0>$ directions) due to its hexagonal close packed (hcp) unit cell.

Tensile deformation in cast Mg alloys with defects has been investigated recently [11,25,26]. Song et al. conducted *in situ* experiments on die cast AM50 alloys and observed how the material around pores and bifilms deforms in tension. Only after stress exceeds yield strength, there was noticeable deformation around pores and bifilms. Song et al. also stated that (i) the final fracture is probably not due to cracking and/or decohesion of the β-phase ($Mg_{17}Al_{12}$) and (ii) the alloy could withstand large amount of plastic deformation before fracture although the presence of structural defects reduced the elongation to only 6%. For the same alloy, Lee et al. [27] found a strong correlation between elongation and area fraction of porosity on the fracture surface. The fracture path was observed to go through the regions of clusters of structural defects. Lee et al. stated that the defect-free elongation for the alloy with $\sigma_Y \approx 120$ MPa should be 29%. Weiler and Wood investigated the effect of pore area fraction on the elongation and tensile strength of AM60B alloy castings via experimentation [25] and finite element modeling [26]. As can be expected, they found that elongation is reduced significantly with increasing size of pores. They also attempted to estimate elongation when the area fraction of pores is zero, i.e., when the specimen is defect-free, by extrapolating the elongation – area pore fraction relationship to zero pores. For a specimen with $\sigma_Y \approx 130$ MPa, they estimated the defect-free elongation, $e_{F(max)}$, to be 10%. A similar approach was taken by Lee and Shin [8] and Lee [9] for AZ91 alloy castings. In these studies, elongation was correlated to the level of microporosity [8] and grain size [9]. Lee and Shin developed a critical strain model, which predicted $e_{F(max)}$ to be between 6 and 10% for $\sigma_Y = 125$ MPa, which agrees with the results of Weiler and Wood. Lee [9] extrapolated elongation-area pore fraction relationships for various grain sizes and found that for $\sigma_Y = 125$ MPa, defect-free elongation can be estimated as:

$$e_{F(max)} = 13.6 \exp(-1.3 \times 10^{-3} d) \tag{2}$$

Lee also suggested that the effect of grain size on elongation should become less pronounced with decreasing level of porosity.

The use of elongation as a measure of the structural quality of aluminum castings was proposed by one of the authors and his coworkers [19,28]. Comparison of current elongation to defect-free elongation, estimated from work hardening characteristics [29] was proposed as a quality index. However, structural defects affect the work hardening characteristics significantly in cast aluminum alloys [30,31]. Therefore, using work hardening characteristics of specimens with defects to estimate defect-free properties was found [19] to significantly underestimate $e_{F(max)}$. Subsequently, one of the authors and his coworkers used hundreds of data from the aerospace and premium castings literature for Al-7% Si–Mg [32], A206 [33] and A201 [34] to estimate $e_{F(max)}$. Because yield strength is minimally affected by structural defects, yield strength is plotted in the x-axis with e_F on the y-axis. A linear relationship between yield strength and elongation was found [14] for all alloys:

$$e_{F(max)} = \beta_0 - \beta_1 \sigma_Y \tag{3}$$

where β_0 and β_1 (MPa^{-1}) are alloy-dependent coefficients although the linear relationships for the three alloys are very similar. Therefore, the quality index, Q_T, can then be found by;

$$Q_T = \frac{e_F}{e_{F(max)}} = \frac{e_F}{\beta_0 - \beta_1 \sigma_Y} \tag{4}$$

Tiryakioğlu and Campbell [14] have recently suggested that there are three regions for Q_T: (1) Q_T is below 0.25, (2) Q_T is between 0.25 and 0.70, and (3) Q_T is above 0.70. In Region 1, premature fracture is due to "old", coarse oxide bifilms which are typically the skins of ingots. In this region, engineers need to focus on melt quality to eliminate old oxides from remelts. Chilling the melt can increase the quality marginally. In Region 2, the molten metal which is free from major "old" oxides but there are "young" oxide bifilms which are entrained during molten metal transfers and mold filling. Chilling can freeze bifilms in the beginning of the process which can increase the properties of the metal. When Q_T is above 0.70, every small detail of the melt preparation and mold filling system design needs to be reviewed. In this region, chilling, i.e., decreasing secondary dendrite arm spacing (SDAS) has no effect on elongation [17]. For all three regions, Tiryakioğlu and Campbell proposed specific quality improvement efforts.

The approach taken by Tiryakioğlu and coworkers has been applied to Mg alloy castings in this study by collecting large numbers of tensile data from the literature and analyzing elongation versus yield strength.

3. Analysis of data and discussion

In this study, elongation and yield strength data from twenty five independent studies in the literature [35–59] have been reanalyzed. In total, more than one thousand and six hundred data points have been collected and analyzed. Alloys from fifteen commercial alloy families as well as a binary alloy have been included. As indicated above, elongation (y-axis) data have been plotted versus yield strength (x-axis). The plot for all data is presented in Fig. 1. Note that there are many specimens at low ductility levels ($\leq 5\%$), especially when yield strength exceeds 100 MPa. Therefore, it is easy to understand why low ductility is assumed to be intrinsic in Mg castings. Fig. 1 also shows that for a particular level of yield strength, number of data points becomes sparse with increasing elongation. The number of points that can be considered maximum at any given yield strength level is approximately 25. Therefore, less than 2% of all data included in this study represent maximum elongation values.

In Fig. 1, maximum points seem to have linear trend with yield strength, similar to what was reported for Al alloys. The line that