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Tensile properties of high-pressure die-cast AM60 and AZ91 magnesium alloys on microporosity variation

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Abstract The effect of microporosity on the variability in the tensile properties of high-pressure die-cast AM60 and AZ91 alloys was investigated, together with a theoretical prediction based on a constitutive model. The strain rate sensitivity of both alloys was measured through an incremental strain rate change test at room temperature, and the microporosity was measured through quantitative fractography analyses on the fractured surface. The variability in the tensile strength and elongation of both alloys can be empirically described as a power law relationship in terms of the microporosity variation. The defect susceptibility of the UTS and elongation to the microporosity variation in the AZ91 alloy is slightly higher than that in the AM60 alloy. The constitutive prediction on the tensile properties of the AM60 and AZ91 alloys is in good agreement with the experimental results, and it suggests that the defect susceptibility of the tensile properties to the microporosity variation is significantly decreased with the increase of strain hardening exponent.

Introduction

Magnesium alloys have been steadily spotlighted as a potential material for the achievement of effective weight-savings in the automotive industry, with the lowest density among the structural metallic materials and their high specific strength. Moreover, the excellent castability of magnesium alloys allows the massive applications to the automotive structural components such as the seat frame, steering wheel, and instrument panel, through various pressure die-casting processes. Given that the internal casting defects such as the micro-voids and shrinkage holes are perfectly unavoidable in the conventional casting process, the effect of casting defects on the variability in the mechanical properties of castings have been frequently studied as an important matter in several researches [1–4].

Among them, the quantification of load carrying capacity to the external load has been recognized as very important factor on the description of stress distribution inside a material. Given that the shape and distribution of micro-voids in a casting are very random and irregular, the volumetric porosity obtained from the bulk density measurement or two-dimensional microstructure observation cannot but present very limited information on the shape and distribution of micro-voids [1, 3, 4]. This is particularly true in the case where the micro-voids are locally clustered or have a high aspect ratio. Gokhale et al. [1] reported that the tensile properties of the AZ91D alloy could be exactly described by the fractographic porosity on the fractured surface, rather than by the volumetric porosity based on the measurement of bulk density [5, 6]. Moreover, in a sequential study on the AM50 alloy, he and his colleagues clarified the dependence of tensile properties on the variation in microporosity and the accuracy on the description of load carrying capacity by quantitative fractography [2].

Similarly, the effect of microporosity on the mechanical properties of aluminum alloys has been also steadily studied until a recent date [3, 4, 7–9]. In particular, Surappa et al. [7] emphasized that the tensile properties of Al–7%Si–0.4%Mg alloy are affected by a concomitant degradation of the plastic deformation in a region neighbor to micro-void by the cracking of eutectic Si-particle, as well as by the distribution

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aspect and shape of micro-voids [8, 9]. Moreover, Cáceres et al. [3, 4] verified the effect of microporosity on the tensile properties, through a constitutive prediction with systematic experiments on Al–7%Si–0.4%Mg alloy. They reported that the theoretical prediction could well predict to the tensile deformation of Al–Si alloy on the microporosity, together with a simple constitutive prediction which did not take into account the strain rate sensitivity [3, 4].

However, Ghosh suggested that the stress distribution neighbor to internal discontinuity depends very sensitively upon the variation of strain rate sensitivity as well as the strain hardening ability and load carrying capacity, especially in low value of strain hardening exponent [10]. Furthermore, given that most of metallic material has very low strain rate sensitivity but not practically zero at room temperature [11], the constitutive prediction for accurate estimation of plastic deformation should take account of the strain rate sensitivity-term [10, 12]. The present study aims to investigate the dependence of the tensile properties on the microporosity variation of high-pressure die-cast AM60 and AZ91 alloys, together with a constitutive prediction for the defect susceptibility of tensile properties to microporosity variation.

Experiment procedure

Specimen preparation

The raw materials used were commercial grade AM60B and AZ91D alloys (Norsk Hydro Co.). The test specimen was fabricated by high-pressure die-casting process. The die-casting machine was a cold chamber type (300 tons) machine which used the manual melt transfer method. The high speed of the plunder was 4.5 m/sec with a stroke length of 250 mm. And, the shielding gas had a mixed composition [CO_2 (25%) + dry air (74.5%) + SF_6 (0.5%)], and the holding temperature of the melt was 660–670 °C.

The pre-heating temperature of molds was about 200–240 °C, according to the position on the fixed mold or the movable mold. The shape of tensile specimen was the cylindrical type, and the length and diameter of its gauge section were 30 mm and 6 mm, respectively.

Tension test and measurement of microporosity

The tension test in this study was carried out at room temperature, under conditions of a strain rate of 2.7×10^{-4} s^{-1} with an extensometer. And, the measurement of the strain rate sensitivity was carried out by the incremental strain rate change method [11] at room temperature. The initial strain rate was identical to that in the static tension test, and a second strain rate was 2.7×10^{-3} s^{-1} and it was applied at an engineering strain of 1.0%. The strain hardening exponent was measured by a linear fit to the slope between the true stress and strain on a log–log scale [12], and the nominal value of the strain hardening exponent was expressed as an average value for the entire specimen.

Given that the bulk density cannot accurately describe the variation in load carrying capacity inside the material [1, 2, 8, 9], the microporosity-terms used in the present study were measured from the quantitative fractography analyses through scanning electron microscope (SEM) observation on each fractured surface for all tensile specimens. And, the area fraction of micro-void was expressed in terms of a ratio between the micro-void area and the entire cross-sectional area of the fractured surface.

Constitutive model and defect susceptibility to microporosity

The theoretical prediction on the dependence of tensile property to microporosity variation was based on Ghosh's constitutive model. The simple power relation between the true stress and strain can be expressed, in terms of the strain rate sensitivity and strain hardening exponent as following Eq. 1 [10].

$$\sigma = K\varepsilon^n \varepsilon\acute{\varepsilon}^m \tag{1}$$

where σ and ε are true stress and true strain and $\acute{\varepsilon}$ is the true strain rate, i.e., $(\partial\varepsilon/\partial t)$ in numerical form. And, n and m represent the strain hardening exponent and strain rate sensitivity, which are numerically defined in Eqs. 2a and 2b, respectively.

$$n = (\partial ln\sigma/\partial ln\varepsilon)_{\acute{\varepsilon}.T} \tag{2a}$$

$$m = (\partial ln\sigma/\partial ln\acute{\varepsilon})_{\varepsilon.T} \tag{2b}$$

Figure 1 shows a schematic geometry of internal discontinuity such as micro-void. As shown, with an assumption that the material contains an area fraction of micro-void, f is under local axial stress equilibrium, the stress distribution can be expressed as Eq. 3 [3, 4].

$$\sigma_i A_i e^{-\varepsilon_i} = \sigma_h A_o e^{-\varepsilon_h} \tag{3a}$$

$$\sigma_i(1-f)A_o e^{-\varepsilon_i} = \sigma_h A_o e^{-\varepsilon_h} \tag{3b}$$

where A_o means the total cross section area to tensile loading ($A_i = A_o(1–f)$), and σ_i,ε_i and σ_h,ε_h are the true stress and strain in the void region and outside the void region, respectively.

Combining Eqs. 1 and 3, the constitutive equation for the stress distribution is given as following Eq. 4.

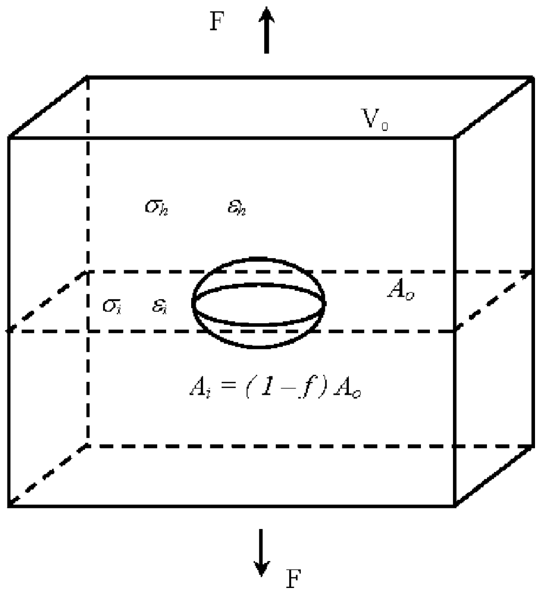

Fig. 1 Schematic diagram of the geometry for the existence of micro-void assumed for modeling

$$(1-f)e^{-\varepsilon_i}\varepsilon_i^n\acute{\varepsilon}_i^m = e^{-\varepsilon_h}\varepsilon_h^n\acute{\varepsilon}_h^m \tag{4}$$

And, the Eq. 4 can be re-written to general form in a time-independent by a differentiation of the time interval as following Eq. 5 [10].

$$(1-f)^{1/m}e^{-\varepsilon_i/m}\varepsilon_i^{n/m}d\varepsilon_i = e^{-\varepsilon_h/m}\varepsilon_h^{n/m}d\varepsilon_h \tag{5}$$

From Eq. 5, the relative increment of $\Delta\varepsilon_i$ on the variation of $\Delta\varepsilon_h$ can obtain as a typical form of the strain profile between the strain within the void region ε_i and strain outside the void region ε_h, by Newton–Raphson iteration method.

On the other hand, given that the true uniform strain is corresponded to the strain hardening exponent ($\varepsilon = n$) at a maximum stress condition, the critical maximum stress, σ_f* can be expressed as following equation, from a combination with the simple power form shown in Eq. 6 [3, 4].

$$(\sigma_f^*/\sigma^*) = (\varepsilon_h^*/\varepsilon_i)^n = (\varepsilon_h^*/n)^n \tag{6}$$

where ε_i^* is the premature true strain which has a microporosity f, and σ^* and ε_h are the maximum true stress and elongation of sound material, respectively. On the viewpoint of tension instability, the numerical form for the calculation of UTS is divided into two derivatives for the relative magnitude between the strain hardening exponent n and true uniform strain ε_h, as following Eqs. 7a and 7b.

$$\sigma_f^*/\sigma^* = (\varepsilon_i^*/\varepsilon_h)^n \quad (\varepsilon_h < n) \tag{7a}$$

$$\sigma_f^*/\sigma^* = (\varepsilon_i^*/n)^n \quad (\varepsilon_h \geq n) \tag{7b}$$

For the variability of the tensile properties on the microporosity variation, Gokhale et al. suggested that the dependence of tensile elongation can describe in terms of a power law relationship, and it can be numerically expressed as the defect susceptibility to the microporosity-term as following Eq. 8 [2].

$$e = e_o[1-f]^\alpha \tag{8}$$

where e is the tensile elongation at an area fraction of f. And e_o is the tensile elongation of a defect-free condition. The α(means the index of defect susceptibility which describes the dependence of tensile elongation on the variation of area fraction of micro-void [9, 13]. Also, the defect susceptibility of tensile strength to the variation of area fraction can be expressed as following Eq. 9.

$$S = S_o[1-f]^\beta \tag{9}$$

where s and s_o are the tensile strengths at a microporosity of f and at a defect-free condition, respectively.

However, there are some arguments on description of relationship between tensile strength and area fraction. Gokhale et al. proposed that the UTS of A356 alloy could be expressed as linear trend on the area fraction of micro-void [9]. Otherwise, Cáceres et al. reported that the tensile strength of A356 alloy has a nonlinear dependence on the variation of microporosity [3, 4]. And, Herrera and Kondic reported that the tensile strength of Al–13%Si and Al–10%Si alloy depend nonlinearly on maximum pore length in the fractured surface [8].

Moreover, as shown in Eq. 6, the tensile strength containing the area fraction of f depends basically on tensile strain-term which is decided by strain related factors and f-value. Therefore, the tensile strength can describe a power law relationship on the microporosity variation, and the overall dependence is indicated by defect susceptibility of tensile strength, β [9, 13].

The power law relation between tensile properties and area fraction of micro-voids in Eqs. 8 and 9 can express as a linear trend in log–log format [9]. The maximum value of tensile properties at a defect-free condition and the defect susceptibility to microporosity variation can obtain empirically from an intercept and a slope of linear trend in log–log format.

Experimental results

Fratography and tensile properties of AM60 and AZ91 alloys

Figure 2 exhibits the SEM views on the fractured surface of a high-pressure die-cast AM60 (a) and AZ91 (b) alloys.

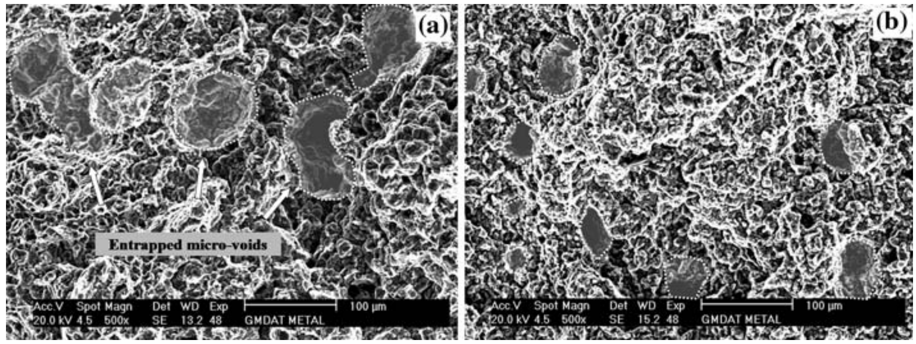

Fig. 2 SEM views on the interdendritic shrinkage voids and entrapped gas holes in high-pressure die-cast AM60 (**a**) and AZ91 (**b**) alloys

The fractured surfaces of both alloys are composed of the facet surfaces showing the fracture of the $Mg_{17}Al_{12}$ precipitate along with the entrapped gas holes and interdendritic shrinkage voids. Also, these figures indicate that the interdendritic shrinkage voids around the entrapped gas hole has higher area fraction, than that of the entrapped gas holes. Moreover, the deformed area of the α-Mg matrix in the AM60 alloy has relatively higher fraction than in the AZ91 alloy.

Figure 3 exhibits the variation of the yield strength of the AM60 and AZ91 alloys on the microporosity variation. As shown, the yield strengths of both alloys decrease linearly with the increase of area fraction of micro-void, i.e., the decrement of load carrying capacity ($\sigma = \sigma_o - \Delta f$) [9]. And, the yield strength of the AZ91 alloy has more sensitive dependence to the area fraction of micro-void, than that of the AM60 alloy. Moreover, it indicates that the maximum yield strength of AM60 and AZ91 alloys in a defect-free condition are 126 and 158 MPa, respectively.

Figure 4 shows the dependence of UTS (a) and elongation (b) on the area fraction of micro-void in both alloys. As shown, the UTS of both alloys has similar dependence on the area fraction of micro-void, with a power law relationship. Likewise, the elongation of both alloys exhibits power law relationship on the variation of area fraction of micro-void. As the area fraction of micro-void increases to about 0.2, the elongation of AM60B alloy is remarkably decreased from 15 to 4%, whereas the elongation of AZ91 alloy is decreased from 8 to 1%.

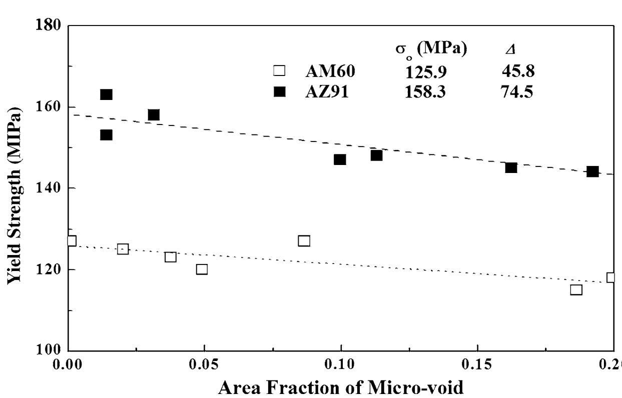

Fig. 3 Variation of the yield strength of high-pressure die-cast AM60 and AZ91 alloys on the variation of area fraction of micro-void

Defect susceptibility of tensile properties to variation of load carrying capacity

Figure 5 shows the variability in the UTS (a) and elongation (b) of the AM60 and AZ91 alloys on the microporosity variation, plotted in the format of ln (*s* or *e*) versus

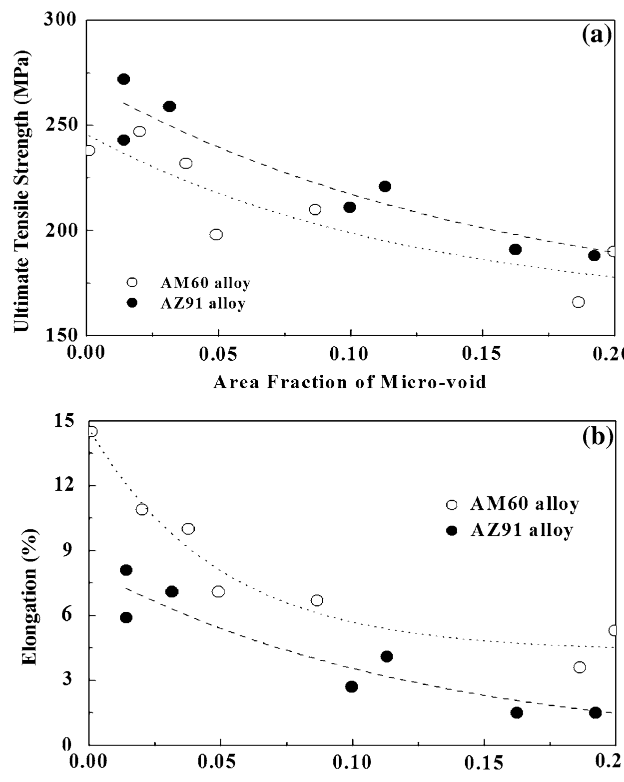

Fig. 4 Dependence of the UTS (**a**) and elongation (**b**) of high-pressure die-cast AM60 and AZ91 alloys on the variation of area fraction of micro-void

[–ln(1–*f*)] [1, 2]. As shown, the variability in the UTS and elongation of both alloys has linear dependence on the microporosity variation. And, it reveals that the elongation of the AM60 alloy indicates higher value than that of the AZ91 alloy, while the UTS of the AZ91 alloy is higher than that of the AM60 alloy.

From linear relationship in Fig. 5, the maximum values of the UTS and elongation in a defect-free condition and the defect susceptibility of tensile properties to the microporosity variation are listed in Table 1. For the tensile properties of a defect-free condition, the maximum elongation of the AM60 alloy is about 11.8%, and this value is much higher value than that of the AZ91 alloy. Furthermore, the defect susceptibility of tensile elongation to the microporosity variation in the AM60 alloy is lower than that in the AZ91 alloy, while the defect susceptibility of tensile strength to the microporosity in the AM60 alloy has a similar level to that in the AZ91 alloy. This means that the tensile elongation of the AZ91 alloy is more sensitive to the existence of micro-voids than that of the AM60 alloy.

And, Table 2 shows the strain rate sensitivity and strain hardening exponent of the AM60 and AZ91 alloy. The

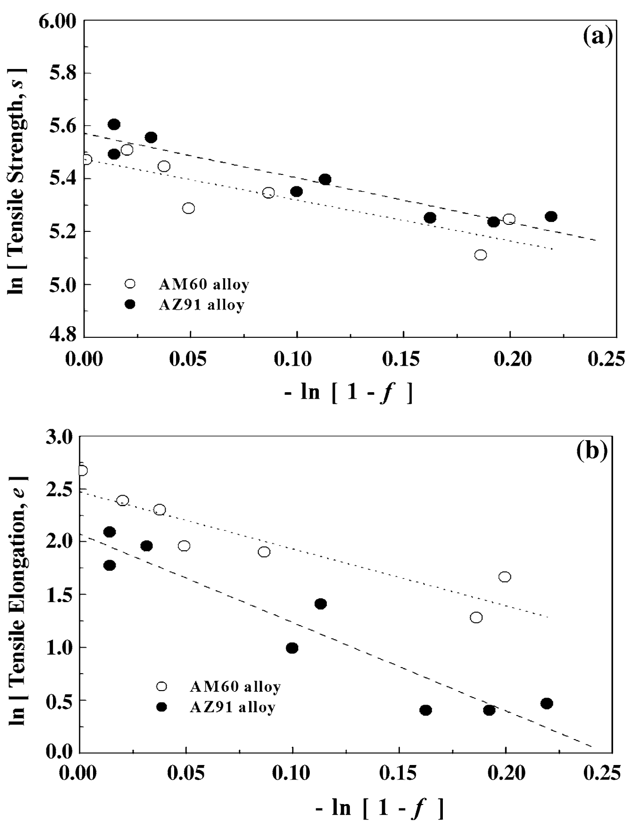

Fig. 5 Defect susceptibility of UTS (**a**) and elongation (**b**) of high-pressure die-cast AM60 and AZ91 alloys to the variation of fraction of micro-void in log–log format

Table 1 Defect susceptibility to microporosity variation and the typical values of tensile strength and elongation in a defect-free condition

Alloy	Defect susceptibility to microporosity		Maximum values in a defect-free condition	
	α	β	e_o (%)	s_o (MPa)
AM 60	5.4	1.6	11.8	238.5
AZ 91	8.4	1.7	7.9	263.0

Table 2 Typical values of the strain hardening exponent and strain rate sensitivity of high-pressure die-cast AM60 and AZ91 alloys

	Strain hardening exponent *n*	Strain rate sensitivity *m*
AM60	0.25 ± 0.02	0.005 ± 0.001
AZ91	0.18 ± 0.02	0.004 ± 0.001

strain rate sensitivities of the AM60 and AZ91 alloy are very low level and indicate almost same level, i.e., about 0.005. Since the strain rate sensitivity of most metallic materials at room temperature is very low, i.e., below 0.015 [11] but not zero, the constitutive equation indicates that the practical contribution of load carrying capacity to the tensile deformation is relatively lower than an assumption that strain rate sensitivity is zero. Therefore, the constitutive model should be taken account of strain rate sensitivity for exact theoretical prediction of tensile properties [10].

For the effect of strain rate sensitivity on tensile elongation, Mabuchi et al. reported that the fine-grained AZ91 alloy exhibits a super plastic behavior with increasing strain rate sensitivity, up to 0.4–0.5 at elevated temperature [14]. Also, Verma et al. and Lee et al. reported that some Al alloys exhibit the super plastic elongation in a range of strain rate sensitivity over 0.3, by the dislocation glide mechanism [15, 16].

On the other hand, the typical value of strain hardening exponent of the AM60 alloy is 0.25, which is relatively higher than 0.18 of the AZ91 alloy. For the strain hardening ability on the tensile deformation, Ghosh suggested in his theoretical study that the defect susceptibility of tensile properties is remarkably decreased as the strain hardening exponent increases. According to Ghosh's constitutive model, this difference of strain hardening exponent between both alloys can practically influence on the tensile properties with regard to the microporosity variation.

Figure 6 shows the dependence of the UTS (a) and elongation (b) on the microporosity variation, together with a constitutive prediction. As shown, the constitutive predictions on the UTS and elongation of both alloys are in good agreement with the experimental results. Moreover, it is noted that the constitutive prediction can very accurately

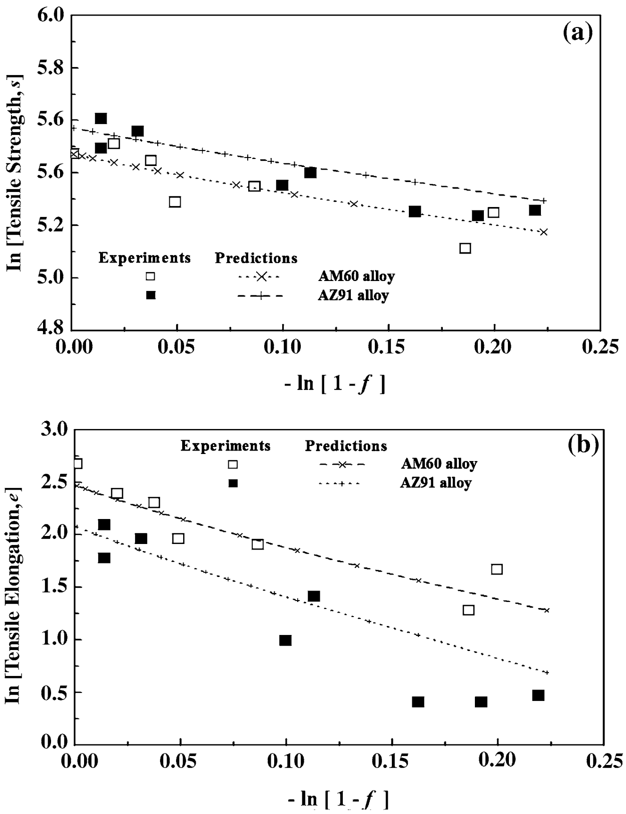

Fig. 6 Constitutive predictions on the dependence of the UTS (**a**) and elongation (**b**) of high-pressure die-cast AM60 and AZ91 alloy on the variation of area fraction of micro-void

predict not only the overall trend of tensile properties on the microporosity, but also the defect susceptibility to the microporosity variation itself.

Discussion

Dependence of tensile properties on load carrying capacity

For the quantification of load carrying capacity, Gokhale et al. suggested the tensile properties of the AZ91 alloy could be more accurately described by the measurement of microporosity through quantitative fractography on the fractured surface than by bulk density [1]. Moreover, he and his colleagues proved clearly in sequential experimental studies that the fractographic microporosity measured in the fracture surfaces of the tensile specimen is much larger than the volumetric porosity based on the corresponding bulk microstructure [9, 13]. Also, Herrera and Kondic reported that the yield strength of Al–12%Si alloy has a linear relationship on the variation of fractographic porosity, whereas it exhibits a constant level with regard to the variation of bulk porosity. In the present study, the UTS and elongation of the AM60 and AZ91 alloys have power law dependence on the area fraction of micro-void, while the yield strength shows a linear trend with the increase of the area fraction of micro-void. Thus, the accuracy of description on dependence of tensile properties on load carrying capacity depends basically upon the method how it exactly estimate the load carrying capacity for tensile loading.

In particular, the complicated morphology of casting defects such as micro-voids may lead to error in the estimation of load carrying capacity, and may eventually lead to misunderstanding and controversy for the practical role of micro-voids as typical stress concentration factors on mechanical properties. Therefore, the quantitative measurement using SEM fractography and stereological techniques can be recommended as an effective methodology for the exact measurement of load carrying capacity.

Defect susceptibility of tensile properties on microporosity

The defect susceptibility of tensile properties to the variation in microporosity had suggested by Gokhale et al. in recent. They reported that the defect susceptibility of tensile properties to microporosity can empirically describe as a power law relationship, through systematic experiments on A356 aluminum alloy [9], AM50 [2] and AE44 magnesium alloys [13].

In the present study, the defect susceptibility of tensile strength to the microporosity variation of the AM60 and AZ91 alloys indicates almost similar value, although the maximum tensile strength of both alloys in a defect-free condition exhibits a practical difference, i.e., about 25 MPa. In contrast, the defect sensitivities of tensile elongation to microporosity variation in the AM60 and AZ91 alloys are 5.4 and 8.4, respectively, and they indicate lower values than 10.3 of the AM50 alloy [2].

However, the maximum elongations of the AM60 and AZ91 alloys in a defect-free condition are 11.8 and 7.9%, respectively. These values are practically lower than 29% of high-pressure die-cast AM50 alloy [2]. This means that the dependence of tensile elongation on the microporosity variation in the AM60 and AZ91 alloys are less sensitive than in the AM50 alloy, although their maximum elongations in a defect-free condition are lower than that of the AM50 alloy [2].

Constitutive prediction on defect susceptibility to microporosity

Ghosh suggested in his theoretical study on tensile instability that the plastic deformation depends remarkably

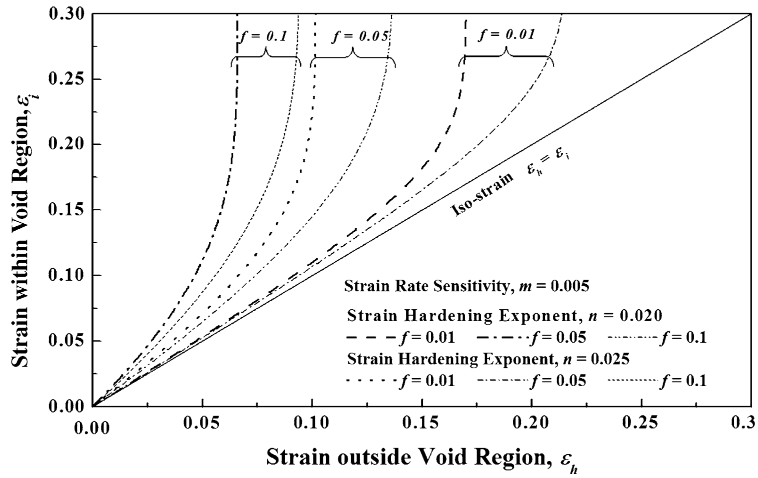

Fig. 7 Typical contribution of strain hardening exponent on the strain profile calculated from constitutive model for a given value of $m = 0.005$

upon the strain hardening ability, no less than that for a practical range of microporosity. And, from his constitutive model, it is well known that the overall contour of the strain profile becomes closer to the iso-strain line with the increase of strain hardening exponent. This means that the tensile strain will come up to that of a defect free material with the increase of strain hardening exponent.

Figure 7 exhibits schematically the dependence of strain profile on the variation of strain hardening exponent for a given value of strain rate sensitivity ($m = 0.005$). As shown, the strain profile is remarkably deviated from the iso-strain line which means a strain profile of defect-free material, even in low strain level as the microporosity increases. In contrast, the inflection point on the strain profile increases along the iso-strain line up to a high strain region as the microporosity decreases. Moreover, this figure indicates that there is a remarkable difference between each strain profiles, despite of a small difference of the strain hardening exponent between 0.20 and 0.25.

For the contribution of strain hardening exponent to the strain profile, Fig. 8 shows the dependence of the UTS (a) and elongation (b) on the microporosity variation of the AM60 alloy for several values of strain hardening exponent at a given value of $m = 0.005$. As shown, the constitutive prediction suggests that the slope of the tensile properties on the microporosity variation increases more sensitively as the strain hardening exponent increases. This means that the defect susceptibility of tensile properties to the microporosity variation is gradually decreased as the strain hardening exponent increases. In particular, as shown in Fig. 8b, the defect susceptibility of tensile elongation to the microporosity exhibits a higher dependence on the variation of strain hardening exponent, than that of the tensile strength. Thus, the constitutive prediction based on Ghosh's constitutive model can exactly predict the defect susceptibility of the tensile properties to the microporosity variation, as well as the overall dependence of the UTS and elongation on the microporosity variation.

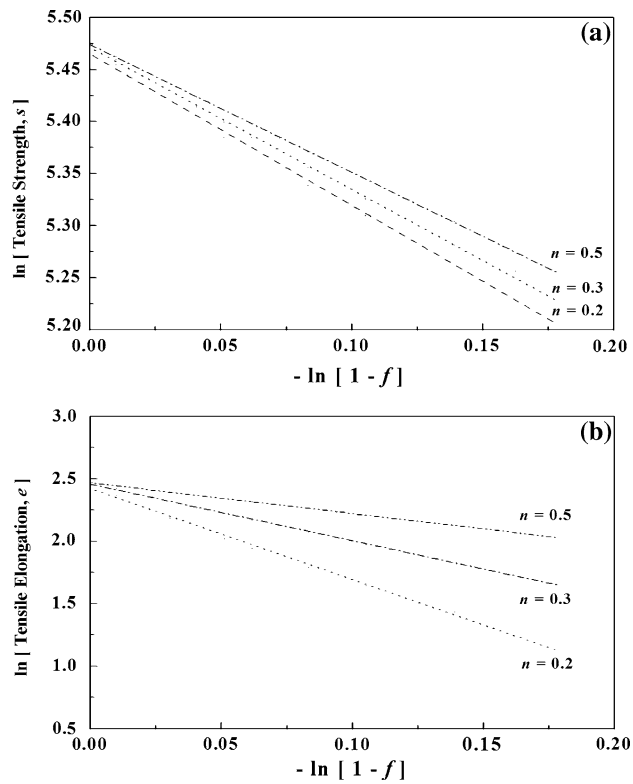

Fig. 8 Constitutive predictions on the defect susceptibility of UTS (**a**) and elongation (**b**) to the microporosity variation of the AM60 alloy on the variation of strain hardening exponent for a given value of $m = 0.005$

Summary

1. The variability in the tensile properties of high-pressure die-cast AM60 and AZ91 alloys can be well described in terms of the variation of load carrying capacity such as the area fraction of micro-void. The UTS and elongation of the AM60 and AZ91 alloys have power law relationship with the microporosity variation, whereas the yield strength of both alloys

exhibits a linear dependence on the microporosity variation.

2. The defect susceptibility of UTS and elongation to the microporosity variation in the AZ91 alloy exhibits a higher value than in the AM60 alloy.
3. The constitutive prediction can predict very well the defect susceptibility of tensile properties to the microporosity variation, as well as the overall trend on the tensile properties of high-pressure die-cast AM60 and AZ91 alloys. And, it suggests that the defect susceptibility of tensile property to the microporosity variation is significantly affected by the variation of strain hardening exponent.

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