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Effect of geometric array of eutectic silicon particles and microscopic voids on the tensile behaviour of a cast aluminium alloy

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ABSTRACTS

The present study aims to investigate the dependence of tensile properties on the microporosity variation of A356 alloy through a modified constitutive model that considers the strain-related factors and the geometric array of micro-voids and eutectic silicon particles, in comparison with the original Ghosh constitutive model. The tensile strength and elongation of the as-cast and T6-treated alloys on the microporosity variation can be theoretically described as an inverse power relationship in terms of the geometric array of the eutectic silicon particles and micro-voids and the strain-related factors such as the strain hardening exponent and strain rate sensitivity. The theoretical prediction by the modified constitutive model is in very good agreement with experimental results, typically for T6-treated alloy, even though the predicted values using the original Ghosh model exhibit a slight difference when compared with the experimental results. However, the theoretical prediction of the tensile properties of the as-cast alloy can predict values similar to the experimental results by considering the plastic constraint factor for the geometric array of the eutectic silicon particles based upon the crack propagation path. The modified constitutive model can yield various strain profiles between the strain within and outside the void regions with respect to the variation of the plastic constraint factor, which considers the geometric array and the size distribution of both constituents even at same area fraction of the micro-voids and eutectic silicon particles. The contribution of the strain hardening exponent to tensile elongation in the modified constitutive model becomes more significant than that of the original constitutive model, because of the additional contribution to the plastic constraint factor describing the geometric array of the micro-voids and eutectic silicon particles.

1. Introduction

The fracture mechanism of Al–Si series alloys is fundamentally based on the nucleation and growth of internal voids and the coalescence between voids with the penetration of ligament [1–15]. In particular, the existence of stress concentration factors such as the micro-voids and shrinkage holes promotes the void growth and coalescence process accompanying the variation of load-bearing capacity inside a material. In terms of the void growth and coalescence mechanism, the geometric array and the size distribution of micro-voids and the strain-related factors describing plastic deformation can be considered as decisive factors for micro- and macroscopic fracture. For the theoretical prediction of tensile deformation behaviour of a material having micro-voids, the Brown–Embury model, Thomason model and Ghosh constitutive model have been proposed as typical theoretical models, and the prediction accuracy of these models depends intimately upon the scientific description of the load-bearing capacity, the crack propagation mode, and the stress condition [14,17,18,22–30].

Among these models, the original form of the Ghosh model suggested that the tensile elongation of a material having micro-voids depends upon the strain-related factors such as the strain hardening exponent and the strain rate sensitivity as well as the nominal value of microporosity [2,3,15,18,26]. This means that the defect susceptibility of tensile properties on microporosity variation is also concerned with the strain-related factors as well as the microporosity. However, even though the Ghosh model can relatively accurately predict the tensile strain compared with other theoretical models [2,3,17,25], it has a restriction that the limit fractured strain achievable in the defect-free condition should be experimentally determined by the variation of the microporosity only, without consideration of the geometric distribution such as the size of micro-voids and the spacing between micro-voids. This is, the original Ghosh model cannot help but suggest only a single value of tensile elongation which determined by a nominal value of microporosity, even in a material which is practical different on

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the size of micro-void or the spacing between micro-voids. In recent, the modified constitutive model which take into account the geometric array and the size distribution of internal discontinuities was suggested in our previous study [26]. This model was suggested as an integrated form that includes the plastic constraint factor which considers the geometric array and the size distribution of the microstructural constituents such as the eutectic silicon particles as well as the micro-voids, and Rice–Tracey equation for the lateral velocity of void growth, and the strain-related factors [26]. For the tensile elongation of T4-treated A356 alloy, it was reported that the theoretical prediction by the modified constitutive model could very accurately estimate the dependence of tensile elongation on the microporosity variation, in comparison with that by the original Ghosh model. Nevertheless, the scientific validity and the usefulness of the modified constitutive model are still required the further verifications and validations on other alloys and conditions.

Therefore, the present study aims to verify the scientific validity of the modified constitutive model through comparison between the predicted values and experimental results on the as-cast and T6-treated A356 alloys using the modified constitutive model previously proposed. In addition, this study aims to investigate the dependence of the plastic constraint factor on the variation of the crack propagation path in terms of the fracture mechanism of Al–Si alloy and the relative contribution of the plastic constraint factor of the micro-voids and eutectic silicon particles to the tensile properties, comparing those of the strain-related factors.

2. Modified constitutive model for void coalescence mechanism

The overall dependence of tensile properties on the microporosity variation in some light alloys such as the aluminium and magnesium alloys has been investigated in many previous studies on the experimental and theoretical approaches [1–24,26–30]. Among them, typically, Ghosh's constitutive model has been used to predict theoretically the tensile properties of a material containing the pre-existed voids in several studies [2,3,10–12,26–30]. For a spherical void existed in the homogenous cross-sectional area by a microporosity, f as shown in Fig. 1, Ghosh's constitutive equation can be described as following Eq. (1), in terms of the relative increase ($\Delta\varepsilon_i$ and $\Delta\varepsilon_h$) of the strain within void region (ε_i) and outside the void region (ε_h) [18]:

$$\Delta\varepsilon_h = (1-f)^{1/m} e^{-\varepsilon i/m} \Delta\varepsilon_i[(\Delta\varepsilon_i/m) n(\varepsilon_i^{n/m-1}) \\ -(\Delta\varepsilon_i/m)(\varepsilon_i^{n/m}) + \varepsilon_i{}^{n/m}]/[e^{-\varepsilon h/m}\varepsilon_h^{n/m}] \quad (1)$$

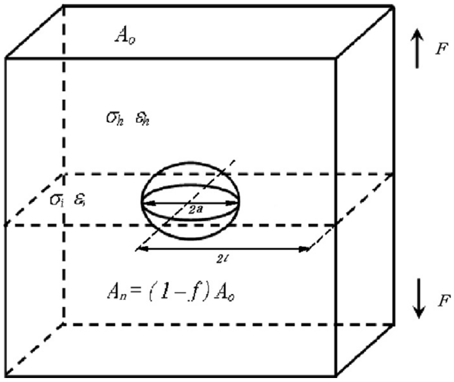

Fig. 1. Schematic view for the geometric array of a micro-void existed in a material for modified constitutive model.

where n and m are the strain hardening exponent and strain rate sensitivity, respectively.

Ghosh's constitutive model can predict relatively more accurate tensile elongation compared with the Brown–Embury model [14,17,23] or Thomason model [25] for void coalescence mechanism, because it takes fundamentally into account the strain-related factors such as the strain hardening exponent and strain rate sensitivity as well as the microporosity-term [26].

Nevertheless, given that the microporosity-term in the original Ghosh model is considered as only a nominal value for the entire micro-void area, there is a restriction that the predicted value for the tensile elongation cannot precisely reflect the distribution aspect of micro-voids with regard to the variation in the size of and the spacing between micro-voids. In addition, Ghosh's approach for the prediction of tensile elongation was achieved through the selection of a limit fractured strain on the strain profile between the strain within and outside the void region [2,3,10–12,28–30]. Practically, the limit strain can be obtained from the maximum strain achievable in the defect-free condition through extrapolation of the experimental results [2,3,18,30]. This approach is difficult to support the scientific meaning and the physical definition of the stable and unstable deformation on the strain profile between the strain within and outside the void region. Furthermore, given that the constitutive model itself includes the strain-related factors describing the plastic deformation behaviour, it is reasonable that the maximum tensile strain of a material should be described as an extreme strain for unstable or quasi-stable deformation on the strain profile, rather than a limit fractured strain [26].

On the other hand, the load bearing capacity-term in the modified constitutive model is composed of the plastic constraint factor describing the geometric array of internal discontinuities such as the micro-voids and eutectic silicon particles in the fractured surface, with the numerical expression for lateral void growth between ligaments, i.e. Rice–Tracey equation, and the numerical formula of the modified constitutive model can be expressed as following equation [26]:

$$\Delta\varepsilon_h = (1-(A_{f-void}/P(\alpha)_{-void} \\ + A_{f-Si\ particle}/P(\alpha)_{-Si\ particle})(a/a_o)^2 e^{\varepsilon i})^{1/m} e^{-\varepsilon i/m}\Delta\varepsilon_i[(\Delta\varepsilon_i/m)(\varepsilon_i^{n/m}) \\ -(\Delta\varepsilon_i/m) n(\varepsilon_i^{n/m-1}) - \varepsilon_i^{n/m}]/[e^{-\varepsilon h/m}\varepsilon_h^{n/m}], \quad (2)$$

where A_f-terms are the area fraction of the micro-void and eutectic silicon particle, respectively. And, a and a_o are the diameter of a micro-void after and before tensile deformation, respectively, and eventually, (a/a_o) is the Rice–Tracey equation describing the lateral velocity of void growth [23,26]. In addition, $P(\alpha)$ is the plastic constraint factor, i.e. a numerical index that is described by the size (a) of and the spacing (l) between micro-voids or eutectic silicon particles, and its numerical expression is the same as Eq. (3) [25]:

$$P(\alpha) = [\alpha(n))/(a/l)^2 + 1.24/(a/(a+l))^{0.5}], \quad (3)$$

where $\alpha(n)$ has a functional relationship with the strain hardening exponent (n), i.e., $0.1+0.217n+4.83n^2$ [23–26,31]. In terms of the pre-mature fracture of internal discontinuities during the plastic deformation, the microstructural constituents such as the eutectic silicon particle have an important contribution on the plastic deformation by additional decrease of the load bearing capacity [10,19–21], comparing with the micro-voids as a primary source [1–15]. In particular, the practical variation on the shape and volume fraction of microstructural constituents such as Al–Fe–Mn and Al–X series compounds as well as the eutectic silicon particles had been considered as a major factor changing the plastic deformation behaviour of a material condition having same microporosity but different microstructural characteristics, for examples, the as-cast and T6-treated condition [33,34].