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Effect of strain rate on the defect susceptibility of tensile properties to porosity variation

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ABSTRACT

The contribution of the strain rate to the dependence of tensile properties on the microporosity variation in A356 casting alloy was investigated in terms of the defect susceptibility of tensile properties to the microporosity variation with variations of the strain rate as well as the relative contribution of microporosity and strain rate to overall tensile properties. The test samples were prepared using a low-pressure die-casting process and subsequent T4 treatment (12-h at 540 °C), and the tensile test was carried out at room temperature for strain rates varying in the 1.4×10^{-4}~1.4×10^{-1} s^{-1} range. The overall dependence of tensile properties on the strain rate is not described precisely owing to remarkable deviations in the data that mainly arose from the variation of the fractographic porosity; these deviations can be clearly attributed to the variability in the defect susceptibility coefficient of the tensile properties to the microporosity variation. The defect susceptibility coefficient of ultimate tensile strength (UTS) to microporosity variation increases with the strain rate, whereas the defect susceptibility coefficient of elongation decreases. Although the UTS for the sample with a low microporosity level increases with increasing strain rates, the UTS above a certain porosity level is affected adversely and decreases with the increasing strain rates. However, the nominal level of tensile elongation on the variation of the strain rate clearly decreases with the increase of the microporosity. The fractographic porosity practically decreases with the increase of the strain rate, and the overall fracture path between the micro-voids depends practically upon a certain transition of the fracture mode of Si particles accompanying the variation of the strain rate. Additionally, the damage evolution of eutectic Si particles is transited from a mixed mode of cracking and debonding failure to a failure mode which the debonding failure dominates as the strain rate increases.

1. Introduction

The existence of micro-voids in conventional casting alloys plays a significant role in the degradation of the overall mechanical properties and has been considered to be a decisive factor, restricting wide-ranging applications of these alloys in heavy duty components in various industries. Therefore, many experimental and theoretical studies have recently been conducted on the effect of internal discontinuities on the mechanical properties of Al-Si alloys [1–6]. As a typical example of these studies, Gokhale et al. quantitatively described the overall dependence of tensile properties on the porosity variation in some Al-Si series casting alloys in terms of a power law relationship between the defect susceptibility coefficient of the tensile properties to the microporosity variation and the maximum value achievable in a defect-free condition given by

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

where e is the tensile elongation of a material with the microporosity f, e_o is the maximum elongation of a defect-free material, and a is the defect susceptibility coefficient of the tensile elongation to microporosity variation and it may consider as a quantitative index how sensitive the tensile elongation is to the microporosity variation [3,4]. Fig. 1 shows graphically the physical meaning of defect susceptibility coefficient and the maximum value achievable in a defect-free condition, based on the experimental results [7]. As shown in Fig. 1(b), the nominal values of defect susceptibility coefficient and maximum elongation are evaluated from the slope and y-axis intercept in a linear expression of logarithmic relationship between the tensile elongation and microporosity variation. Additionally, Eq. (1) can describe the dependence of tensile strain on fractional variation of other internal discontinuities or stress concentration factors such as the damaged 2nd phase particles and non-metallic inclusions as well as micro-voids [5–10].

Similarly, the ultimate tensile strength (UTS) can also describe in terms of power law dependency on the microporosity variation, as the following Eq. (2) [5,6].

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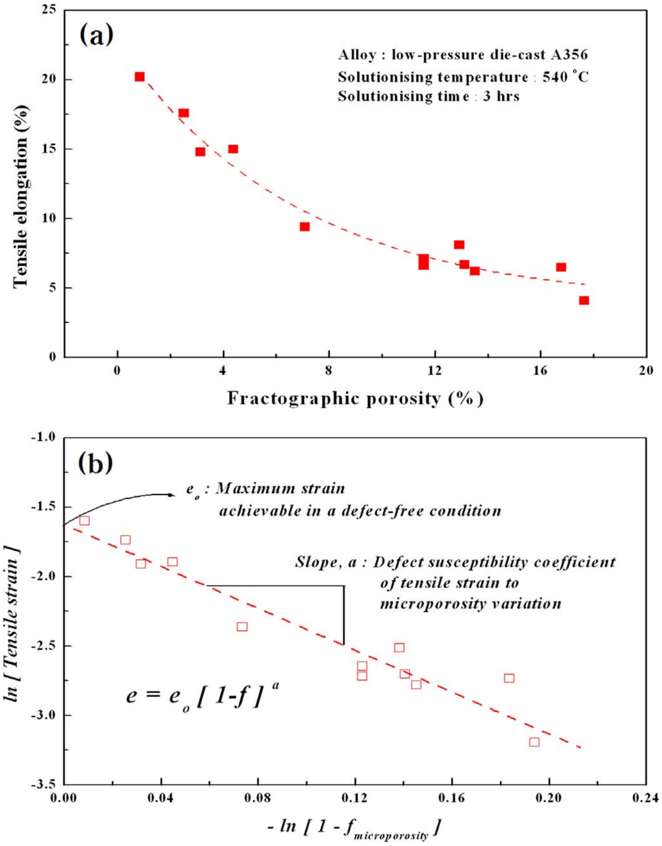

Fig. 1. Graphical definition of defect susceptibility coefficient and maximum strain in a defect-free condition from power relationship between tensile elongation and microporosity variation.

Table 1
Chemical composition of A356 aluminium alloy.

Elements Composition (wt%)	Si	Mg	Mn	Cu	Fe	Ti	Sr	Al
A356	7.34	0.33	0.06	0.09	0.29	0.05	0.02	Bal.

Table 2
Nominal values of the microstructural characteristics of as-cast and T4-treated A356 alloy.

Microstructural features	Nominal values	
	As-cast alloy	T4-treated alloy
Fraction of Si particles	21.7	11.2
Secondary dendrite arm spacing, SDAS (μm)	36.4	44.7
Spacing between Si particles in colony (μm)	1.6	5.6
Aspect ratio of Si particles	1.91	1.66
Circularity of Si particles	0.55	0.67

$$s = s_o [1\text{–}f]^b \tag{2}$$

where s is the UTS of a material with a microporosity f, s_o is the UTS of a defect-free material; and b is the defect susceptibility coefficient of the UTS to microporosity variation.

On the other hand, the constitutive relationship of tensile deformation is definitely described by the interplay of the strain, strain rate, and temperature [8–13]. This means that the strain rate and temperature make significant additional contributions to the strain deviation arising from the porosity variation on the deformation behaviour of a material. Nevertheless, most of the previous studies on the quantification of tensile properties in terms of the defect susceptibility coefficient and maximum values did not take the additional contribution of the strain rate into account [3–6]. In particular, to date, the physical significance of the strain rate for the overall dependence of tensile properties on the microporosity variation has been rarely evaluated.

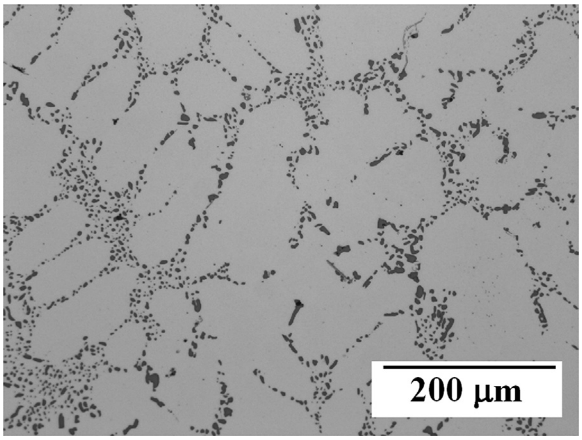

Fig. 2. Typical microstructural view of the T4-treated A356 alloy.

Therefore, the present study aims to investigate the practical contribution of the strain rate to the overall dependence of the tensile properties of casting alloys with micro-voids, in terms of the defect susceptibility coefficient of tensile properties to microporosity variation and the relative contribution of microporosity and strain rate to overall tensile properties.

2. Experiments

2.1. Specimen preparation and microstructural observation

The raw material used in the present study was a commercial A356 alloy, and the chemical composition of the alloy is listed in Table 1. The test specimens were prepared from a position perpendicular to the circumference of the rim in the form of an automobile wheel (20-in. dia. with 10 spokes) fabricated through a low-pressure die-casting process.

The test specimens were prepared by the T4 treatment (solution treatment: 12 h at 540 °C). Typical microstructural characteristics, such as the area fraction of eutectic Si particles, secondary dendrite arm spacing (SDAS) and the interspacing between Si particles in eutectic Si colony, were quantitatively measured using an optical microscope (O.M.) and a 2-colour contrast image analyser. The applied etchant used was a Keller-type solution (2%HF+3%HCl+5% HNO_3+distilled water).

2.2. Tension test and measurement of microporosity

The tensile specimen was fabricated as a plate type with a gauge length of 30 mm and a width of 6 mm and was fabricated approximately 10 pieces for each condition. The tension test was carried out at room temperature under strain rate conditions of 1.4×10^{-4}~1.4×10^{-1} s^{-1} using an extensometer (Instron 5582 model). The yield strength, UTS, and fracture elongation were chosen as the typical tensile properties, and the nominal value of the yield strength was measured as the stress level at 0.2% offset strain.

Microporosity was measured through quantitative fractography analyses using scanning electron microscopy (SEM, JEOL JSM-5600 model) observations on the fractured surface of the entire test specimen, and the value was expressed as the area ratio of the micro-voids to the entire area of the fractured surface. Additionally, the average micro-void size and the spacing between the micro-voids on the fractured surface were measured via image analysis of SEM observations.