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Ductile fracture locus of AC4CH-T6 cast aluminium alloy

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ABSTRACT

Purpose: Cast aluminium alloys have found wide application to manufacture lighted-weight components of complex shape in automotive and aerospace industries. To improve the strength and ductility of cast aluminium alloys, it is necessary to study their fracture properties by conducting a series of tests. This study addresses calibration of ductile fracture property of the cast aluminium alloy (AC4CH-T6) made by the gravity die casting with sand mold.

Design/methodology/approach: 6 round bar specimens and 6 butterfly specimens are machined from the actual cast component. The tensile tests on the smooth and notched round bar specimens are performed to calibrate the fracture strain in the range of high positive stress triaxialities. The combined loading tests on the butterfly specimens are carried out using a uniquely designed Universal Biaxial Testing Device (UBTD). These tests cover the fracture properties in the rage of low and negative stress triaxialities. Detailed finite element models of all the tests are developed. The fracture locus in the space of the effective plastic strain to fracture and the stress triaxiality are constructed in a wide rage from -1/3 to 1.0.

Findings: It is found that material ductility sharply decreases with the stress triaxiality. The material ductility at the negative stress triaxiality is much higher than that in the positive stress triaxiality.

Research limitations/implications: Large spread of data is observed for those tests repeated on the same loading configuration, necessitating the statistical analysis of the fracture processes.

Practical implications: It is expected that such a fracture criterion would be able to correctly predict the fracture response of actual cast aluminum components under complex loading in the practical applications.

Originality/value: The conventional researches focused on the material ductility at the stress triaxiality larger than +1/3. The present study showed the material ductility at the wide range of stress triaxiality from -1/3 to 1.0.

Keywords: Ductility; Cast aluminium alloy; Stress triaxiality; Ductile fracture locus

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ENGINEERING MATERIALS PROPERTIES

1. Introduction

The microstructure of aluminum casting alloy in this study consists of an aluminum matrix strengthened by MgSi and Si precipitates, dispersing eutectic silicon particles and Fe-rich intermetallics. These microstructures are affected by chemical compositions, solidification time and heat treatment. The effects of those factors on the microstructure were examined [1,4,16,17]. It is well known that the ductility of the gravity die casting aluminum alloys depends on the secondary dendrite arm spacing (SDAS) [5,13]. Wang et al. [20,21] examined the role of the microstructural features such as SDAS in the tensile properties and fracture behavior of the A356/357 alloys. The above investigations give an insight to ductile fracture micromechanisms but are limited to one particular stress triaxiality of about 1/3. Then, the same authors investigated the fracture properties at the wide range of stress triaxiality in a low pressure die cast aluminium alloy and the gravity die castings A356 [8-12,19]. The attempt of the present study is made to calibrate the fracture properties in the wide range of stress triaxiality in another type of gravity die casting aluminum alloy AC4CH-T6 made by sand molding techniques.

A number of fracture criteria have been proposed to describe the material ductility. The ductility is understood here as an intrinsic ability of a material to undergo a certain amount of plastic deformation without fracture. Wierzbicki et al. [2,18,22] critically evaluated a number of ductile fracture models in the space of the effective plastic strain to fracture and the stress triaxiality would be able to show a good correlation with a variety of experiments. Such a fracture locus can be expressed, in a general form, as

$$\bar{\varepsilon}_f = f(\eta) = f\left(\frac{\sigma_m}{\bar{\sigma}}\right) \qquad (1)$$

where $\bar{\varepsilon}_f$ is the effective plastic strain to fracture and η is the stress triaxility defined by the ratio of the mean stress $\bar{\sigma}$ to the equivalent stress σ_m.

In the present paper, a fracture locus is developed for gravity die casting aluminum alloy AC4CH-T6 by combining coupon tests with corresponding finite element analysis. It is expected that such a fracture criterion would be able to correctly predict the fracture response of actual cast aluminum components under complex loading in the practical applications.

Table 1.
Chemical composition of the studied cast alloy (wt %)

Cu	Si	Mg	Zn	Fe
<0.10	6.5-7.5	0.25-0.45	<0.10	<0.20
Mn	Ni	Ti	Pb	Sn
<0.10	<0.05	<0.20	<0.05	<0.05

2. Specimen preparation and test procedures

2.1. Material

The material used for a gravity die casting aluminum component was studied in the present research. The casting was made of an Al-Si-Mg alloy in the sand molding under gravity. The sand molds would give a slower solidification velocity and lead to inferior ductility for the cast alloy than metal moldings because of worse heat conduction ability, e.g. see [15]. The chemical composition of the AC4CH cast aluminium alloy is shown in Table 1. The T6 heat treatment was applied, which is believed to improve the ductility of the castings.

Dozens of metallographic sections in the critical regions of the components were prepared to characterize the microstructure of the prototype of the gravity die casting aluminum alloy. The typical graph taken by a scanning electron microscope (SEM) is displayed in Fig. 1 showing normal aluminum-rich dendrites separated by eutectic regions containing silicon particles. The average SDAS of the present alloy made by sand molding is about 50 micrometer. It is clear that the size of silicon particles in sand-molding cast aluminum alloy is larger than that of metal-molding cast aluminum alloys obtained in the previous study [8-12,19]. A small value of the SDAS usually indicates a good ductility. A total of six round bars and six butterfly specimens were machined from the cast aluminum component.

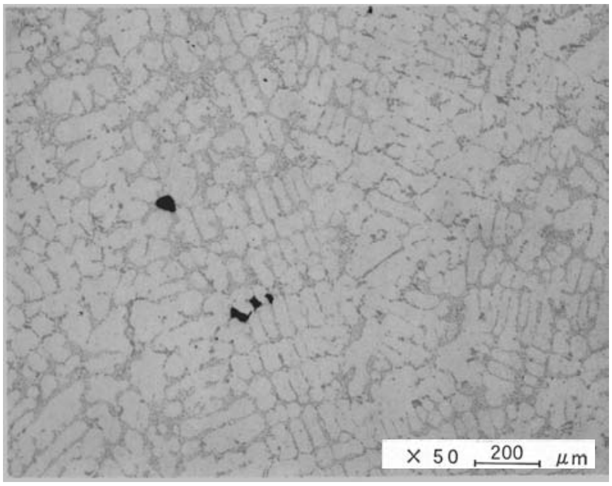

Fig. 1. Micrograph of the microstructure of the present cast alloy

2.2. Test specimens

To construct an empirical fracture locus that covers a wide range of stress states, one has to carefully design specimens and experimental procedures. In this research, two types of test were considered: conventional tensile tests on notched and unnotched round bars, and biaxial loading tests on flat butterfly-like specimens. The former provides information on the fracture properties under tension, represented by high positive triaxialities. The effective plastic strains to fracture in the range of low and negative stress triaxialities were obtained from the biaxial loading experiments.

Three types of round bars including one smooth specimen and two notched specimens were proposed to cover fracture properties in the range of high positive stress triaxialities. For each type, two identical specimens were prepared. The configuration and size of three types of specimens are given in Fig. 2(a)-(c). As a complementary to the tensile tests of the round bars, biaxial loading tests on "butterfly" flat specimens were carried out to characterize fracture properties of the cast aluminum alloys in the rage of negative and low stress triaxialities. This new type of flat specimens were developed by Bao et al. [3] and have been successfully applied to calibrate the fracture loci of A710 steel and 2024-T351 aluminum alloy. This type of specimens has a complex, double curvature geometry in the gauge section such that cracks would initiate in the central region in most of the loading cases. A detailed discussion on the development of this type of specimens can be found in Ref. [3]. The major geometrical size of the new specimens is given in Fig. 3. To ensure that a crack first occurs at the center of the gauge section, the central region has the minimal thickness of 1.0 mm, much smaller than the thickness of the shoulder region 3.0 mm. This is an advantage over conventional flat specimens, in which a crack is often generated at the boundary, particularly under shear. To hold the specimen securely, two long shoulders are designed to provide sufficient gripping area.

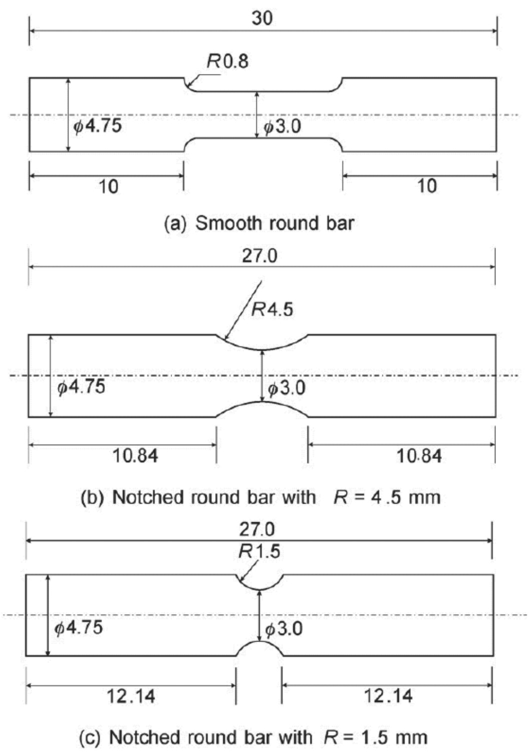

Fig. 2. Dimension of the round bar specimens (unit: mm)

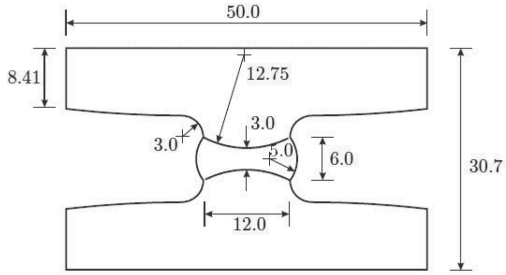

Fig. 3. Major dimensions of the butterfly specimen (unit: mm)

2.3. Test method

To ensure that a crack first occurs at the center of the gauge section, the central region has the minimal thickness of 1.0 mm, much smaller than the thickness of the shoulder region 3.0 mm. This is an advantage over conventional flat specimens, in which a crack is often generated at the boundary, particularly under shear. To hold the specimen securely, two long shoulders are designed to provide sufficient gripping area. The advantage of the new specimen is fully exploited by working with a custom-made Universal Biaxial testing Device (UBTD). Figure 4 illustrates a "butterfly" flat specimen mounted in the UBTD with the orientation angle 10 degree. By suitably changing the orientation of the specimen with respect to the loading direction, different stress states would develop from pure tension, combined tension and shear, pure shear, combined compression and shear, all the way to pure compression. With the UBTD, one would be able to construct a fracture locus in a wide range of stress triaxialities using one type of specimens. Five loading conditions were considered from combined compression and shear, pure shear, to combined tension and shear. The orientation angles of the specimens range from -10 degree to 20 degree. Two pure shear tests were performed to examine the repeatability of experimental data. It is expected that obtained average stress triaxialities would be evenly distributed from -1/3 to +1/3. These two data correspond to uniaxial compression and tension, respectively.

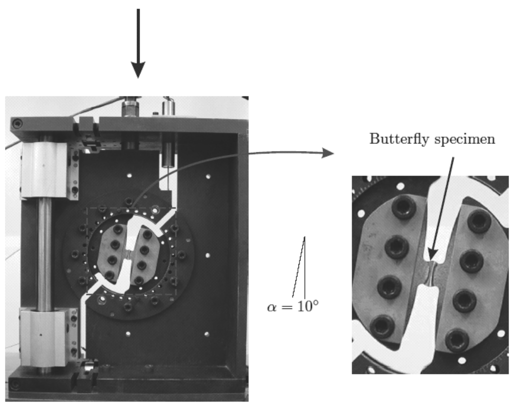

Fig. 4. A butterfly specimen with the orientation angle of 10 degree mounted in the Universal Biaxial Testing Deice (UBTD)

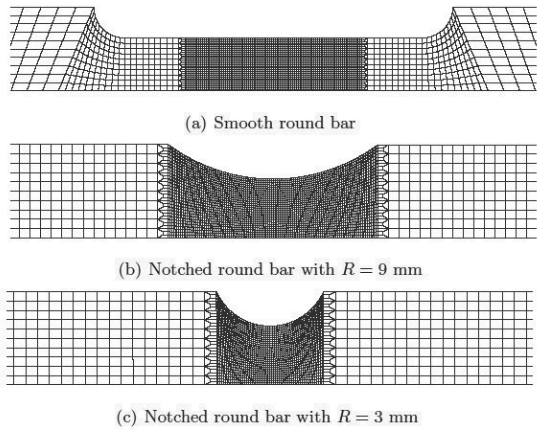

Fig. 5. Finite element models of the round bar specimens

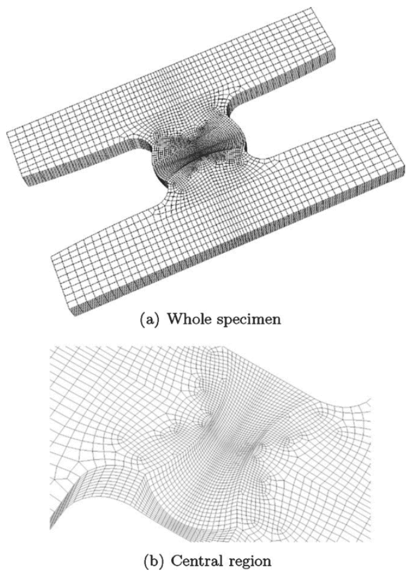

Fig. 6. Finite element model of the butterfly specimen

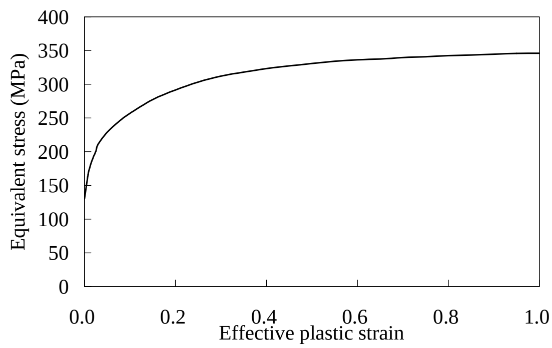

Fig. 7. The true stress-strain curve for the present cast aluminum alloy with the elastic modulus of 86.0 GPa and the Poisson's ratio of 0.33

3. Calibrations of plasticity and fracture properties

3.1. True stress-strain curves

The true stress-strain curve up to fracture, which is basic input data in finite element analysis, need to be first determined from the tests. A trial-and-error method is adopted here by forcing a numerically predicted load-displacement curve to closely match experimental data. In this study, all the tests were modeled numerically with ABAQUS/Standard. For the round bar specimens, two-dimensional finite element models were generated using axisymmetric, four-noded, reduced integration elements (CAX4R), see Figs. 5 (a)-(c). In all the three models, the elements of 0.1 mm x 0.1 mm are defined in the gauge section where necking and subsequent fracture occurs. One end of the models is defined with fixed boundary conditions and a tensile displacement is prescribed at the other end. For the butterfly specimens, a three-dimensional finite element model was built with eight-noded brick, reduced integration elements (C3D8R), see Figs. 6 (a) and (b). The total element number is 39,760. The finest elements of 0.1 mm x 0.1 mm x 0.1mm are located in the central region of the gauge section. Figure 7 shows the calibrated true stress-strain curve for the present AC4CH-T6 cast alloy. This true stress-strain curve describes the strain hardening evolution for a simple isotropic, J2 plasticity model.

3.2. Ductile fracture locus

The tests provide the instant at the point of fracture, represented by the critical displacement of the gauge section. The corresponding finite element analyses give the evolution of stresses and strains of the critical points. By combining the tests and the numerical simulations, one would be able to construct empirical fracture envelopes of materials. In the tensile tests on the round bar specimens, fracture usually initiates at the center of the necking zone. For the biaxial loading tests on the butterfly specimens, it is not clear whether cracks iniate in the middle thickness of the gauge section or on the outer surfaces. Bao et al. [3] compared damage accumulation of both sites and concluded that there was not much difference.

Figures 8 and 9 show the evolution of the stress triaxiality and the effective plastic strain of the critical points up to fracture for the round bars and the butterfly specimens, respectively. It appears that the stress triaxialities vary in a certain range of each test. Without resorting to the damage accumulation rule, the average value of the stress triaxiality is defined in the range $(0, \bar{\varepsilon}_f)$:

$$\left(\frac{\sigma_m}{\bar{\sigma}}\right)_{av} = \frac{1}{\bar{\varepsilon}_f}\int_0^{\bar{\varepsilon}_f} \frac{\sigma_m}{\bar{\sigma}}\, d\bar{\varepsilon}_{pl} \ . \qquad (2)$$

The fracture strain $\bar{\varepsilon}_f$, determined from the numerical simulation, is the effective plastic strain corresponding to the measured displacement to fracture u_f.

Since the stress triaxialities in all these tests vary in a rather narrow range, the definition of the average value would not introduce large errors. This is exactly what the butterfly specimens were designed for.

For practical applications, it would be preferable to use an analytical curve to fit the fracture test data. An exponential function relating the effective fracture strain to the stress triaxiality is commonly used:

$$\bar{\varepsilon}_f = D_1 + D_2 \exp(D_3 \eta) \,, \qquad (3)$$

where three coefficients: D_1, D_2 and D_3 need to be determined. This function was first developed by Rice and Tracey [14] from theoretical analysis of enlargement of a spherical void. Hancock and McKenzie [6] modified the expression on experimental results of round bar tensile tests. Note, that Eq. (3) is better known as the Johnson-Cook fracture criterion [7].

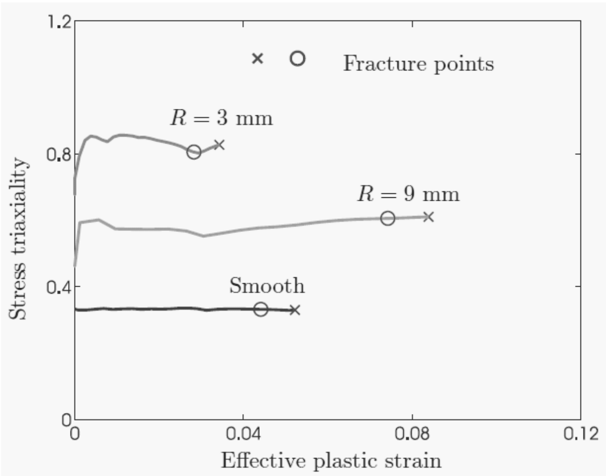

Fig. 8. Evolution of the stress triaxiality and the effective plastic strain of the critical material points for the round bar specimens

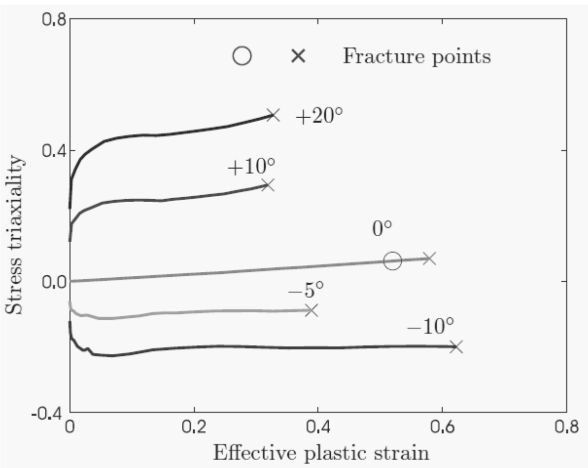

Fig. 9. Evolution of the stress triaxiality and the effective plastic strain of the critical material points for the butterfly specimens

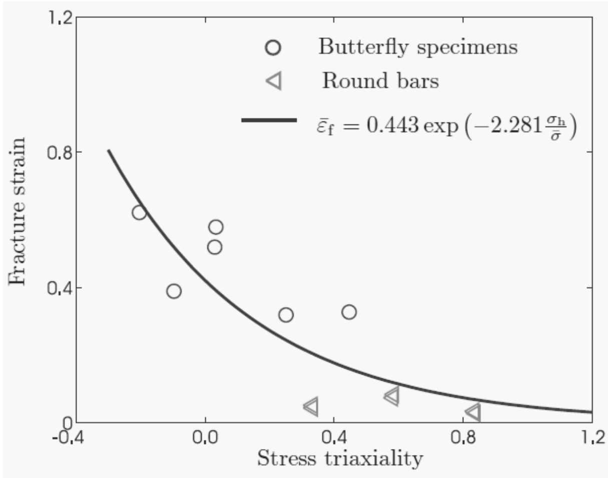

Fig. 10. Calibrated fracture locus of the present AC4CH-T6 cast aluminum alloy

All the fracture points were plotted in Fig. 10 with the stress triaxiality as an independent variable. It appears that the material ductility sharply decreases with the increasing stress triaxiality. The experimental result shows the effective fracture strain reaches 0.622 in the case dominated by compression while the effective fracture strain is as low as 0.03 at the stress triaxiality of 0.83. Clearly, the ductility at the negative stress triaxiality is much higher than that in the positive stress triaxiality. The optimization gives the following material coefficients for the Johnson-Cook fracture loci: D_1 = 0.0, D_2 = 0.443 and D_3 = -2.281, respectively, for the present AC4CH-T6 cast aluminum alloy.

4. Conclusions

In this study, the ductile fracture properties of the cast aluminum alloy AC4CH-T6 made by sand molding were characterized in the form of a fracture locus using a combined experimental-numerical approach. A total of twelve tests were performed including six tensile tests on the round bars and six biaxial loading tests on the flat butterfly specimens, respectively. Corresponding finite element analysis was conducted and the evolution of stresses and strains of the critical points was determined.

The ductile fracture locus was formulated in the space of effective plastic strain to fracture and the stress triaxiality. It appears that there is a very strong dependency of the material ductility of the stress triaxiality on the present AC4CH-T6 cast aluminum alloy. The material ductility is much lower in the positive stress triaxiality than the negative stress triaxiality. A large spread of fracture data was observed. This may be caused by randomly distributed pores. It would be necessary to describe ductile fracture properties of the present cast aluminum alloy in a statistical way for the future study.

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