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Stress-Strain Curves of Pure Aluminum and Al-4.5mass%Cu Alloy in Semi-Solid State

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Abstract

The information of the mechanical properties, such as elastic modulus, is necessary to be calculated the hot tearing by CAE. The stress-strain curves in semi-solid state of pure aluminum and Al-4.5mass%Cu alloy, whose deformation behaviors had been classified into four stages in the previous study, were investigated in this study. Shapes of stress-strain curves in semi-solid state changed with temperature as same as deformation behaviors. Elastic modulus calculated from stress-strain curves were smaller than that calculated by general commercial software. This difference of elastic modulus was about three to five orders of magnitude in Pa. This difference would be caused by the melting of grain boundary and the disappearance of connection between solid phases in general commercial software. Elastic modulus obtained by the stress-strain curve should be more appropriate for calculation of the hot tearing by CAE than that calculated by commercial software.

Introduction

Hot tearing occurs frequently in the direct chill (DC) casting process in practical applications. Many reports on the investigation of the hot tearing mechanism have been published. Watabe and Yoshida et al. reviewed some of these reports and summarized the mechanism in the following words “In the case of a material in the semi-solid state, if the tensile strain or stress generated by solidification shrinkage excesses the strength or the fracture strain of the material, hot tearing will occur.” [1, 2] Recently, some prediction methods for hot tearing have been reported. For example, Morishita reported a prediction method that uses chemical compositions of 3XXX and 5XXX aluminum alloys[3]. However, in order to predict hot tearing with high accuracy, a prediction method that uses CAE needs to be developed. To develop such a prediction method, information on the mechanical properties of materials in the semi-solid state, such as tensile strength, elongation, elastic modulus, and yield stress, is required. It was clarified in the author’s previous study that liquid contributes to the deformation of pure aluminum and Al-4.5mass%Cu alloy (Al-4.5%Cu) in the semi-solid state (in this study, “mass%” has been expressed as “%”) [4, 5]. Therefore, it is necessary to consider the deformation behavior of materials in the semi-solid state for the prediction of hot tearing.
In this study, stress–strain curves of pure aluminum and Al-4.5%Cu in semi-solid state, the mechanical properties of which were investigated in the previous study, were investigated.

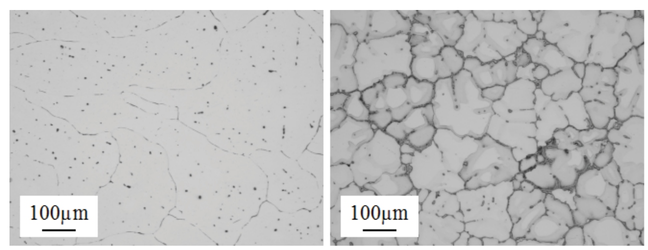
Experimental procedures

Materials and specimen preparation

Pure aluminum (99.7% grade) and Al-4.5%Cu were selected as sample materials. Billets (diameter: 330 mm) of these materials were fabricated by DC casting. The chemical compositions of the fabricated billets are summarized in Table I. For use in the tensile test, plate-type specimens with parallel sections having dimensions of 4 mm (thickness) × 3 mm (width) × 10 mm (length) were fabricated from constant domains of these billets. Fig. 1 shows the microstructures of the specimens. Each microstructure was characterized by dendrites. In addition, compounds observed in grain boundaries and interdendrite arms. The average grain sizes of pure aluminum and Al-4.5%Cu were 196 μm and 153 μm, respectively. The solidi of pure aluminum and Al-4.5%Cu were identified to be at 644°C and 549°C, respectively, by differential thermal analysis (DTA).

Table Ⅰ. Chemical composition of ingot (mass%)

	Cu	Fe	Si	Mg	Ti	Al
Pure aluminum	≦0.01	0.10	0.10	0.01	0.02	Bal.
Al-4.5%Cu	4.44	0.05	0.03	0.01	0.02	Bal.



(a) Pure aluminum (b) Al-4.5%Cu
Figure 1. Microstructures of tensile test specimens.

Tensile test in semi-solid state

A schematic of the instrument used in the tensile test is shown in Fig. 2. The details of the tensile test (such as accuracy of temperature control, estimation method for elongations, and homogenization of micro segregation in heated specimens) have been reported in a previous study [5].

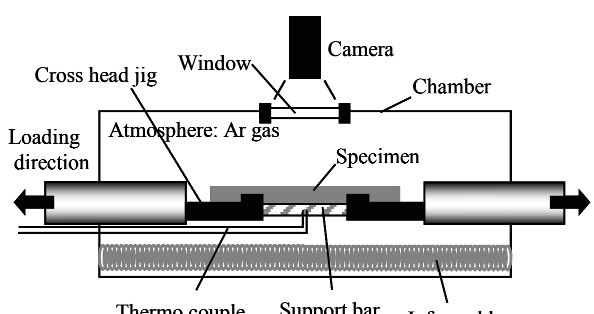


Figure 2. Schematic of tensile test instrument.

Stress-strain curve

The load and distance between crossheads in the tensile test instrument were detected. Stress was calculated by dividing the load by the cross–sectional area of the specimen under loading. The distance between crossheads did not correspond to strain because it included portions other than gage length. In the previous study, the elongation (strain) was estimated by comparing the distance between the gage points before and after the tensile test[5]. In this study, this elongation was assumed to be correct. By assuming that the elongation was proportional to the distance between the crossheads, strain was calculated using the following relation:

$$\varepsilon = (D - D_0) \times \frac{\varepsilon_B}{(D_B - D_0)} \quad (1)$$

where ε is strain, ε_B is breaking strain estimated by comparing the distance between the gage points, D is the distance between the crossheads, D_B is the distance between the crossheads after the completion of the tensile test (when the specimen was broken). A stress–strain curve was constructed using the obtained values of stress and strain.

Elastic modulus

The definition of elastic modulus employed in this study is shown in Fig. 3. The gradient of the stress–strain curve in the elastic region was used as the elastic modulus. However, to eliminate any thermal stress, the specimen was not allowed to contact the jigs before the tensile test. Some idle time existed before the load transfer at the beginning of the tensile test. Therefore, the range in which strain was immediate after the beginning of the tensile test was excluded from the calculations.

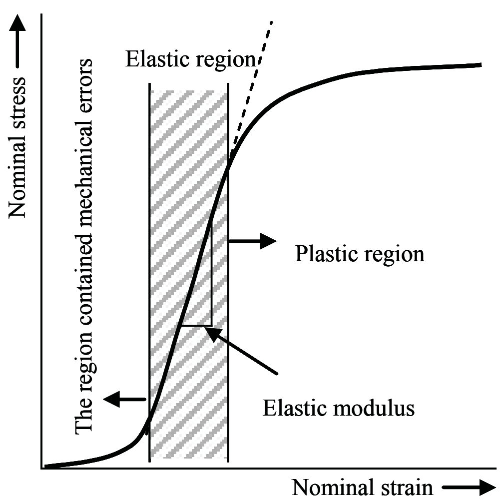


Figure 3. Schematic of definition of elastic region and elastic modulus at stress-strain curve in this study.

Results and discussion

Mechanical properties and deformation behaviors in semi-solid state

The changes in the mechanical properties and deformation behaviors of pure aluminum and Al-4.5%Cu are shown in Fig. 4. In the previous study, it was reported that the deformation behaviors of both these materials in the semi-solid state were classified into four stages (shown in Table Ⅱ) according to their mechanical properties, fracture surface morphologies, and in situ observations made during the tensile tests [5].

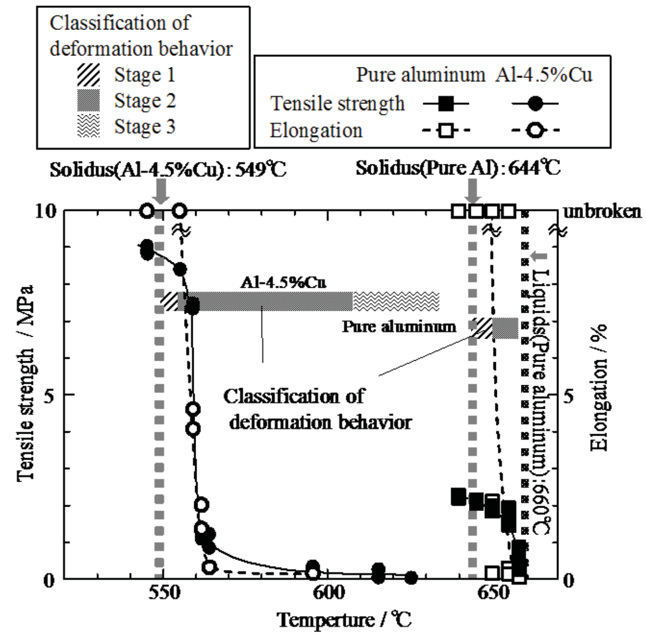


Figure 4. Change in mechanical properties and deformation behaviors of pure aluminum and Al-4.5%Cu.

Table Ⅱ. Classifications of deformation behavior in semi solid state

Stage 1	Large uniform deformation and high tensile strength are obtained.
Stage 2	Embrittlement with liquid film is occurred.
Stage 3	Healing behavior of crack by liquid phase flow is occurred.
Stage 4	Surly zone. Specimen could not keep original shape.

Stress strain curves of pure aluminum

The stress–strain curves of pure aluminum are shown in Fig. 5. The deformation behaviors at these temperatures are classified as stage 2. The stress at 650°C increases linearly with increasing strain. After the maximum stress is reached, the stress decreases slightly. The specimen then breaks by a small increase in the strain. Shapes of the stress–strain curves for 655°C and 658°C revealed that brittle fracture occurred in the elastic region at these temperatures. Brittle fracture was revealed by in situ observations made during the tensile test at these temperatures. The shapes of the stress–strain curves correspond to these results.

Stress strain curves of Al-4.5%Cu

Stress–strain curves of Al-4.5%Cu are shown in Fig. 6. The stress at 555°C (stage 1) increases linearly with increasing strain. After the maximum stress is reached, the stress decreased slightly. At this temperature, the specimen did not break even when the distance between the crossheads was maximum. The appearance of the Al-4.5%Cu specimen before and after the tensile test at 555°C is shown in Fig. 7. Uniform deformation with reduction in the cross-sectional area was observed. It was considered that this reduction in the cross-sectional area caused the slight decrease in stress after the maximum stress was reached.
The shapes of the stress–strain curves for 559°C, 561°C, and 595°C (classified as stage 2) were different. The stress–strain curve for 559°C has a similar shape to that for 650°C of pure aluminum. Further, the stress–strain curve for 561°C has a similar shape to those for 655°C and 658°C of pure aluminum. The gradient in the elastic region of the stress–strain curve for 595°C was significantly smaller than the corresponding gradients at 559°C and 561°C. Moreover, the decrease in stress after the maximum stress was reached was considerably smaller than that at 561°C. In the case of Al-4.5%Cu, the solid–solid contact at the grain boundaries in stage 2 disappeared with increasing temperature [5]. At 559°C, most of the fracture surface showed traces of ductile fracture of the solid. However, the traces of ductile fracture were not observed on the fracture surface at 561°C. Therefore, these differences in the shapes of the stress–strain curves were considered to be caused by the disappearance of the solid–solid contact at the grain boundaries.
At 615°C and 635°C (these temperatures were classified to be in stage 3), the gradient of the stress–strain curves in the initial part became too small with increasing temperature. Further, the breaking strain became large with increasing temperature. In the previous study, crack healing by the liquid phase was observed in situ in the tensile test in stage 3 [5]. Deformation in this temperature range is controlled by the flow of the liquid phase. Therefore, fluid resistance of the liquid phase is included in the gradient in the initial part of the stress–strain curves.

Elastic modulus in semi-solid state

The elastic moduli of pure aluminum and Al-4.5%Cu are listed in Tables Ⅲ and Ⅳ, respectively. The elastic moduli calculated by JMatPro, which is computer modeling software for materials properties developed by Sente Software, are also included in Tables Ⅲ and Ⅳ. The experimentally obtained elastic moduli for these materials were three to five orders of magnitude smaller than those calculated by JMatPro.
For Al-4.5%Cu, the elastic moduli decreased by about 97% in the temperature range 555–595°C. However, the elastic moduli calculated by JMatPro decreased by only 23% in the same temperature range. The constituent phase and elastic moduli calculated by JMatPro are shown in Fig. 8. The elastic moduli calculated by JMatPro decreased rapidly with the melting of Al_2Cu. Then, it decreased slightly with a decrease in the volume

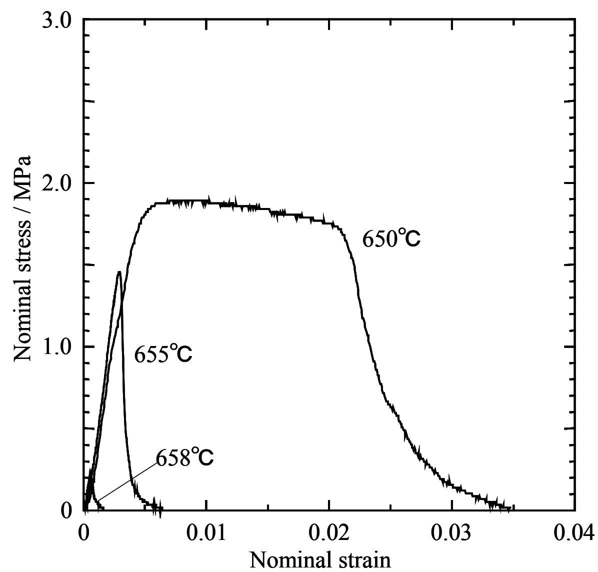


Figure 5. Stress-strain curves of pure aluminum at each temperature.

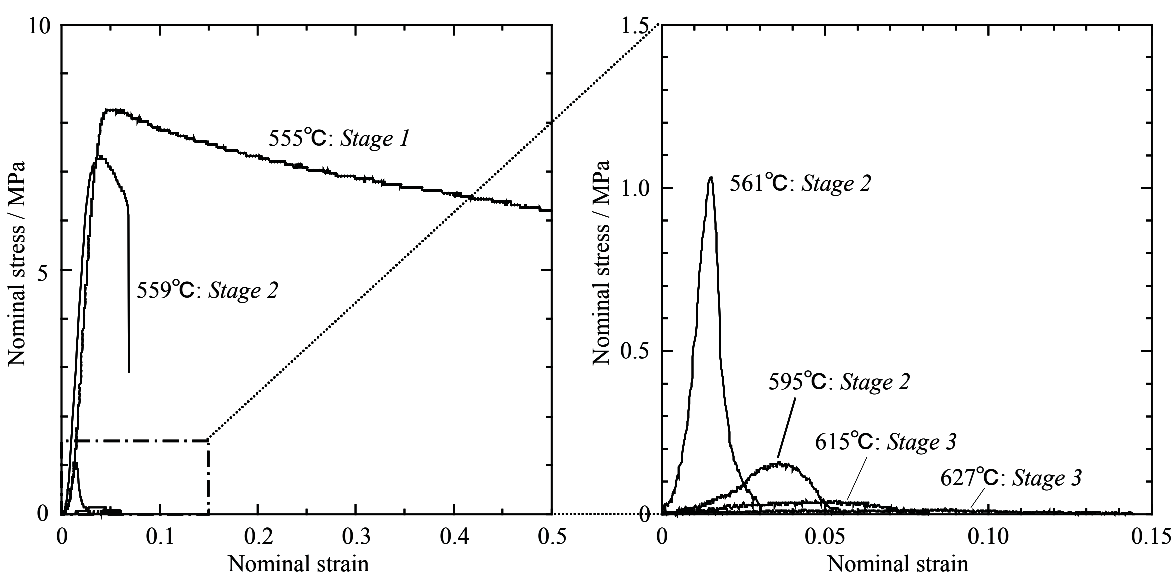
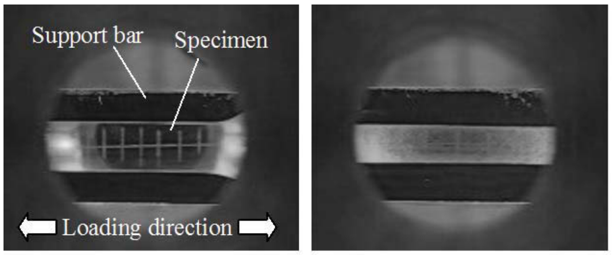


Figure 6. Stress-strain curves of Al-4.5%Cu at each temperature.



(a) Before tensile test (b) After tensile test (unbroken)

Figure 7. Appearance of Al-4.5%Cu specimen before and after tensile test at 555℃.

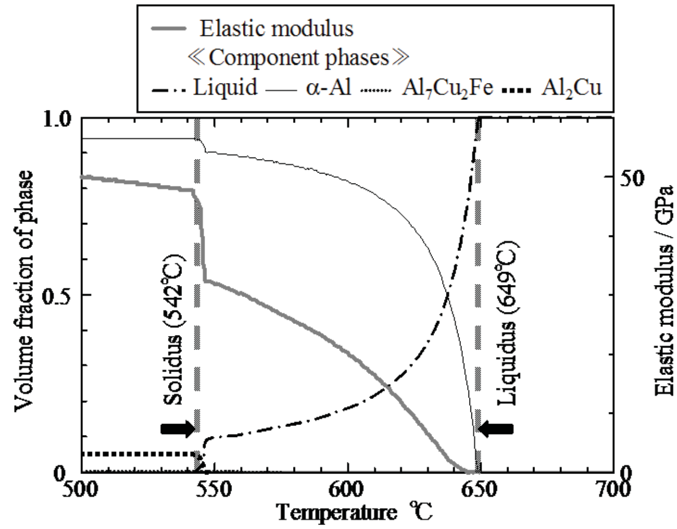


Figure 8. Change in component phases and elastic modulus in Al-4.5%Cu calculated by JMatPro.

Table Ⅲ. Elastic modulus of pure aluminum

Temperature / ℃		650	655	658
Elastic modulus / MPa	Calculated by stress-strain cureve	577	546	544
	Calculated by JMat Pro	33000	23000	7000

Table Ⅳ. Elastic modulus of Al-4.5%Cu

Temperature / ℃		545	555	559	561	564	595
Elastic modulus / MPa	Calculated by stress-strain cureve	338	302	322	143	98	8
	Calculated by JMat Pro	43000	31000	30000	30000	29000	21000

e fraction of α-Al. The elastic moduli were calculated until liquidus at which α-Al completely melted. However, the experimentally obtained elastic moduli of Al-4.5%Cu rapidly decreased in the low or middle temperature range corresponding to the semi-solid state because of the melting of the grain boundaries. Therefore, the disappearance of solid–solid contact at the grain boundaries accompanied by melting should be considered for the calculation of elastic moduli. Further, the experimentally obtained elastic moduli should be used in high-accuracy calculations such as the estimation of hot tearing by CAE.

Conclusions

(1) The stress–strain curve was constructed using the data for load and the distance between the crossheads, which were obtained in the tensile test.
(2) In the semi-solid state, the shapes of the stress–strain curves of pure aluminum and Al-4.5%Cu changed with temperature.
(3) Disappearance of solid–solid contact at the grain boundaries along with melting has to be considered for calculating the elastic moduli. Further, the experimentally obtained elastic moduli should be used in high–accuracy calculations such as the estimation of hot tearing by CAE.

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