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Internal stress behavior of the short ceramic fiber reinforced aluminum alloy under tensile deformation

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Abstract

The in situ measurement of phase stress under tensile deformation on an A6061 alloy reinforced with SiC whiskers (Al/SiCw MMC: Metal Matrix Composite) was performed using the X-ray diffraction technique. In order to raise a preciseness of measurements, we applied a profile fitting technique to separate the nearby located diffraction peak. Tensile deformation on elastic to plastic range was applied by four points bending device and discussed internal stress behavior in the short ceramic fiber reinforced MMC. Phase stress in Al matrix was increased linearly up to 2800×10^{-6} in strain and then saturated immediately. On the other hand phase stress in SiC whiskers shows an unstable stress behavior. It was decreased at first because of the Poisson's effect from Al matrix but reversed over 500×10^{-6} applied strain. The measured phase stress behavior in elastic region agreed with the calculations using micromechanics based on Eshelby/Mori–Tanaka model except for this unstable internal stress region. The macro stress behavior in plastic region was extremely small than that of the tensile test results. It supposed that the mechanism of strength is not so much the fiber reinforcing as the dispersion strengthening like the Orowan mechanism. Regarding the fatigue property, ΔK_{th} of the Al/SiC MMC, this was lower than that of the A6061 alloy. On the Al/SiCw MMC specimen, many micro void formations were observed around the fatigue crack tip even under the ΔK_{th} of A6061. It was considered that these were caused by the high gradient of residual stress on composite process and the unstable stress behavior in low ΔK region.

Keywords: Metal matrix composite; SiC whisker; X-ray diffraction; Peak separation; Profile fitting; Tensile deformation; Internal stress behavior; Phase stress; Micro mechanics; Fatigue crack propagation

1. Introduction

The aluminum alloy reinforced with ceramic short fibers (SF-MMC) has light weight and high wear-resistance properties. Since, it is able to plastically-work easily such as during extrusion, forging or rolling, it is expected there would be significant application for automobile and aero-space fields. However, this material consists of ductile matrix and brittle fibers. The interaction between these components will cause a complex internal stress under tensile state. On the other hand the SF-MMC shows the elastic–plastic behavior during tensile deformation in spite of including brittle fibers. This means strains in each phase in matrix and fibers are different from the macro strain of the SF-MMC. Therefore, it is interesting to measure the stress of each phase (called phase stress) in tensile state to analyze reinforcement and the fracture mechanism of the SF-MMC. In this study, we tried in situ measuring of phase stress in Al matrix and SiC whiskers using by X-ray diffraction technique [1–4] on elastic to plastic deformation range and discussed internal stress behavior of the SF-MMC by comparing experimental data with the calculation results by the micromechanics on Eshelby/Mori–Tanaka model [1,5]. In the X-ray stress analysis, high intensity diffraction and single peak are the necessary condition for precision 2θ measurement. It is well known that Fe Kα X-ray is suitable for the measurement of SiC ceramic. However, the diffraction of SiC phase is close to that of Al phase in the higher 2θ angle range. Therefore, the foot of two peaks is often overlapped and this makes difficulty to determine the base line of back ground noise. In order to raise a preciseness of measurements, profile fitting technique [6] was applied to the diffraction profile for

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the purpose to separate the nearby located peak. In addition, peak separation of Kα double line was performed to the SiC whiskers diffraction for avoiding Kα_1 and Kα_2 duplication owing to its narrow peak width. It is considered the internal stress effect caused by the interaction between whiskers and matrix more influences fatigue properties than the tensile strength. Therefore, we discussed from the viewpoint of fatigue crack propagation too.

2. Theory

2.1. X-ray stress measurement on dual phase material

Bragg angle, $2\theta_{\phi\psi}$, is obtained by diffraction experiment with characteristic X-ray. Subscripts ϕ and ψ are angles which express the orientation of the strain, $\varepsilon_{\phi\psi}$, as shown in Fig. 1.

According to Bragg's law, we have

$$\varepsilon_{\phi\psi} = \frac{1}{2}(2\theta_0 - 2\theta_{\phi\psi})\cot\theta_0 \tag{1}$$

where $2\theta_0$ indicates the diffraction angle at stress free. $\varepsilon_{\phi\psi}$ is a normal strain determined by X-ray method. The fundamental equation for the stress measurement is expressed as following equation [7], when both of matrix and inclusion phases have the isotropic elastic body.

$$\begin{aligned}\varepsilon^i_{\phi\psi} &= \left(\frac{1+\nu}{E}\right)^i_{\mathrm{ph}}(\sigma^i_{11}\cos^2\phi + \sigma^i_{12}\sin 2\phi + \sigma^i_{22}\sin^2\phi - \sigma^i_{33}) \\ &\quad \times \sin^2\psi + \left(\frac{1+\nu}{E}\right)^i_{\mathrm{ph}}\sigma^i_{33} - \left(\frac{\nu}{E}\right)^i_{\mathrm{ph}}(\sigma^i_{11} + \sigma^i_{22} + \sigma^i_{33}) \\ &\quad + \left(\frac{1+\nu}{E}\right)^i_{\mathrm{ph}}(\sigma^i_{31}\cos\phi + \sigma^i_{23}\sin\phi)\sin 2\Psi\end{aligned} \tag{2}$$

The symbol 'i' indicates a phase, for example $i=M$ means matrix and $i=I$ the second phase, E and ν are Young's modulus and Poisson's ratio. The subscript 'ph' means the phase X-ray elastic constant as distinguished from the mechanical elastic constant.

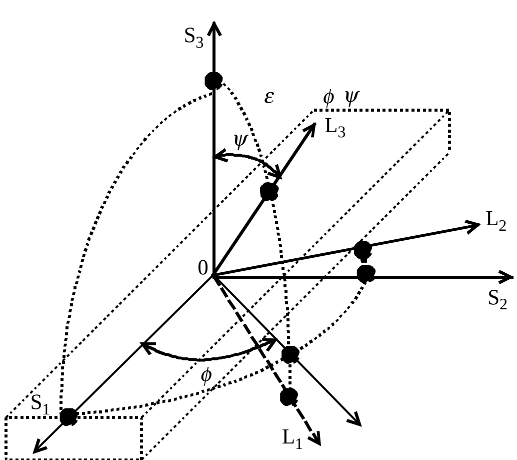

Fig. 1. Coordinate system of X-ray stress measurement.

When $\phi=0$ Eq. (2) leads to

$$\sigma^i_{11} - \sigma^i_{33} = \left(\frac{E}{1+\nu}\right)^i_{\mathrm{ph}}\left(\frac{\partial\varepsilon_{\phi\psi}(\phi=0°)}{\partial\sin^2\psi}\right)^i \tag{3}$$

Eq. (3) can be used to obtain primary stresses from X-ray diffraction data ($2\theta_{\phi\psi}$ and $\sin^2\psi$).

Stresses in individual phases, so-called phase stress, can be obtained directly by applying the X-ray stress measurement method [8]. Applying the above equations and measuring strain $\varepsilon_{\phi\psi}$ in $\phi=0$, 45, 90, 180, 225 and 270°, we obtain all the tri-axial stress components σ_{ij}.

When residual stress generate in the dual phase composite, microscopic state of stress as shown in Fig. 2 is usually built up due to the misfit of physical and mechanical properties between the constituents in the material. The following equations can be deduced from the equilibrium conditions for micro stresses by defining σ^m_{ij}, σ^Ω_{ij} as micro stresses in matrix and in the second phase, σ^M_{ij}, σ^I_{ij} as phase stresses in matrix and in the second phase [9–11],

$$\left.\begin{aligned}\sigma^0_{ij} &= (1-f)\sigma^M_{ij} + f\sigma^I_{ij} \\ \sigma^m_{ij} &= \sigma^M_{ij} - \sigma^0_{ij} \\ \sigma^\Omega_{ij} &= \sigma^I_{ij} - \sigma^0_{ij}\end{aligned}\right\} \tag{4}$$

where f denotes the volume fraction of the second phase.

2.2. Theoretical solution of a phase stress

Using the Eshelby's theory and the Mori–Tanaka method [12], Lin and Mura [13] arrived at the following equations when an ellipse inclusion with the volume fraction f is embedded in an isotropic matrix. (called Eshelby/Mori–Tanaka model)

$$\begin{aligned}\sigma^M &= \sigma^0 + \sigma^m = \sigma^0 - fC(S-I)\{C-(C-C^*)[S-f(S-I)]\}^{-1} \\ &\quad \times [(C-C^*)C^{-1}\sigma^0 + C^*\Delta\varepsilon^p]\end{aligned} \tag{5}$$

$$\begin{aligned}\sigma^I &= \sigma^0 + \sigma^\Omega = \sigma^0 + (1-f)C(S-I)\{C-(C-C^*)[S-f(S-I)]\}^{-1} \\ &\quad \times [(C-C^*)C^{-1}\sigma^0 + C^*\Delta\varepsilon^p]\end{aligned} \tag{6}$$

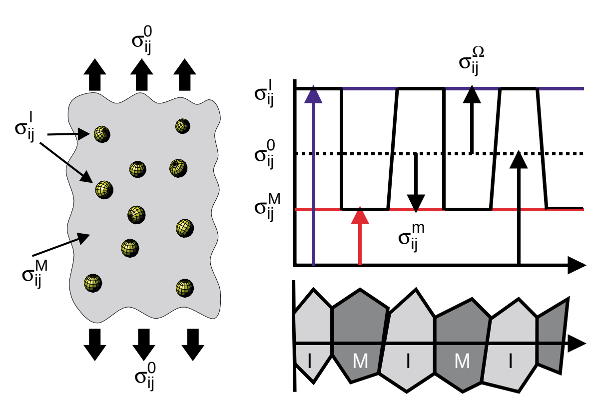

Fig. 2. Status of macro- and micro-stress.