Effects of Loading Velocity on Fracture Toughness of a SiCw/A6061 Composite at Elevated Temperatures

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The influence of loading velocity on the fracture toughness of a SiC whisker reinforced 6061 aluminum alloy composite was investigated at elevated temperatures. A precracked three-point bend specimen configuration was selected for fracture toughness measurement, with tests being conducted at loading velocities of 10^{-2} to $10 \text{ m} \cdot \text{s}^{-1}$, and at temperatures up to 473 K. The results showed that the fracture toughness increases with increasing loading velocity, but the difference with respect to room temperature is small, because the fracture toughness decreases slowly with increasing testing temperature. The composite material failed mainly by whisker pull-out and whisker breaking.

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I. Introduction

Metallic materials, when reinforced with brittle fibers, whiskers or particulates, (metal matrix composites or MMCs), can provide desirable mechanical properties including high specific stiffness, high plastic flow strength, high creep resistance and good corrosion resistance⁽¹⁾⁻⁽⁵⁾. These properties make these kinds of MMCs attractive for a wide range of applications in automobile, aerospace and defense industries. Therefore, a large number of theoretical and experimental studies have been made in recent years⁽⁶⁾⁻⁽¹⁰⁾.

However, it is well known that the deformation and fracture behavior of a material depend on the testing temperature and strain rate, that is under dynamic loading the mechanical behavior of many materials can be quite different compared to that under static loading. For this reason, to design a material resistant to impact loading, dynamic penetration or other dynamic conditions, it is important to understand the behavior of a material at different loading velocities. However, most of the studies on MMCs have been limited to quasi-static low strain rates, and at room temperature. It has been noted that, in addition to the increase in flow stress with increasing loading velocity, there is an increase in tensile elongation⁽⁶⁾⁻⁽⁸⁾. For example, Pickard *et al.*⁽⁶⁾ have noted that the tensile elongation of a SiCw/2124Al composite increased from 3–4% at 10^{-3} s^{-1} to 7–8% at 10^3 s^{-1} at room temperature. Kobayashi *et al.*⁽⁷⁾ found that the crack growth until the maximum load point in the dynamic loading condition is slightly faster than that with static loading. Harding and Taya⁽⁸⁾ found that the SiCw/2124Al composites showed a marked increase in the fracture strain with increasing strain rate. Neverthe-

less, it is important to investigate the fracture toughness and fracture behavior of the composite materials at wider range of loading velocity, especially at elevated temperatures.

Along with a previous study⁽¹¹⁾ at room temperature, the present work was carried out to examine the effects of loading velocity at elevated temperatures on the fracture toughness and fracture behavior of a SiC whisker reinforced 6061 aluminum alloy composite, using a three-point bend specimen with a pre-crack.

II. Material and Experimental Procedures

1. Material and specimens

The material used in the present study was a 6061 aluminum alloy matrix composite reinforced with 22 vol% SiC whiskers, which was fabricated by using a high pressure infiltration technique⁽¹²⁾. The composite was heat treated to the overaged condition⁽⁹⁾⁽¹²⁾. A solid solution treatment was performed at 803 K for 9 ks followed by water quenching, then the material was heated at 450 K for 180 ks.

The pre-cracked three point bend specimens ($4 \times 8 \times 40 \text{ mm}^3$ in size) were machined after heat treatment, with the loading axis parallel to the casting direction. In order to observe the microstructure of the specimens, the surfaces of the specimens were polished carefully before testing. The fatigue precrack was introduced following the standard ASTM E399-90⁽¹³⁾, a/W of which is about 0.55 (a : the crack length and W : the width of the specimen).

2. Experimental procedures

Dynamic fracture toughness tests (loading velocity from 1×10^{-2} to $1 \times 10 \text{ m} \cdot \text{s}^{-1}$) were performed using a

servo-hydraulic high speed testing system (**Fig. 1**). In order to record the true load-time history avoiding oscillations accompanying with inertial loading, strain gages attached onto the specimen (see the enlarged part of Fig. 1) were used in the present study. The deflection signal and the load-time signals from both impact bar and strain gages were measured and directly transferred to a computer system. The tests were conducted in air at 373, 423 and 473 K. The specimens were heated in a resistance furnace with a temperature accuracy of ± 1 K, and kept at the testing temperature for 1.8 ks before starting a test, as mentioned above. In order to avoid the influence of the temperature on the gage factor, the strain gages were calibrated at each testing temperature before doing fracture toughness tests.

3. Measurement of residual stress by using X-ray diffraction

A RIGAKU Geiger Flex system was used to measure the residual stress on the fracture surfaces at different depths from the fracture surfaces as in the previous study⁽¹¹⁾. The residual stress was calculated with the following equation⁽¹⁴⁾:

$$\sigma_r = -\frac{E}{2(1+\nu)} \cot \theta_0 \cdot \frac{\pi}{180} \cdot \frac{d(2\theta)}{d(\sin^2 \psi)} \quad (1)$$

where, σ_r is the residual stress, E is the Young's modules, ν is Poisson's radio, ψ is the angle between the incident X-ray direction and the sample surface normal, and θ_0 is the standard Bragg's diffraction angle.

4. Fracture morphology and microstructure

In order to investigate the fracture behavior under various loading velocities at elevated temperatures, the fracture surfaces of the failed specimens were examined with a scanning electron microscope (SEM). The surfaces of specimens (which had been polished before testing) near the fracture surface were also examined.

III. Results

1. Load-deflection curves

The load-deflection curves with various loading velocities of the present composite material at elevated temperatures, showed the same tendency as those at room temperatures⁽¹¹⁾. These are almost purely elastic up to the maximum load (no evident general yield). It is interesting to note that the maximum impact load does not evidently change within the loading velocity from 10^{-2} to $1 \text{ m} \cdot \text{s}^{-1}$, but it increases remarkably when the loading velocity increases to $10 \text{ m} \cdot \text{s}^{-1}$. **Figure 2** shows typical load-

Fig. 1 Block diagram of the instrumented impact test system.

Fig. 2 Typical load-deflection curves of SiCw/6061Al composite with a loading velocity of $10 \text{ m} \cdot \text{s}^{-1}$ at different temperatures.

deflection curves with a loading velocity of $10 \text{ m} \cdot \text{s}^{-1}$ at different testing temperatures. It can be seen that the maximum load decreases with increasing testing temperature, while the deflection shows no evidently change and the slope of the load-deflection curves decreases with increasing testing temperature.

2. Fracture toughness

Because of the elastic fracture to the loading, it was assumed that the stress-intensity factor K may be determined by linear elastic fracture mechanics⁽¹⁵⁾. According to ASTM E399-90, the fracture toughness K was calculated using the follow equation:

$$K = \frac{SP_M}{BW^{2/3}} f\left(\frac{a}{W}\right) \quad (2)$$

where

$$f\left(\frac{a}{W}\right) = \frac{3(a/W)^{1/2}[1.99 - (a/W)(1 - a/W)(2.15 - 3.93a/W + 2.7a^2/W^2)]}{2(1 + 2a/W)(1 - a/W)^{3/2}} \quad (2')$$

where: P_M is the maximum load which the specimen was able to sustain, S is the span for the three point bend test

and B is the thickness of the specimen. The fracture toughness measurements are shown in **Fig. 3**. It can be

seen that the loading velocity sensitivity of these toughness at elevated temperatures reveals the same tendency as that at room temperature. However, with increasing testing temperature, the loading velocity sensitivity diminished.

On the other hand, the relationship between the fracture toughness and rate of stress intensity factor ($\dot{K} = K/t_m$; t_m is the time to the maximum load⁽¹⁶⁾) at different temperatures is shown in Fig. 4. The variation in fracture toughness with $\dot{K}$ indicates the same tendency as that with loading velocity, and the difference of the fracture toughness decreases with increasing testing temperature.

3. Residual stress

The typical residual stresses distribution along depth from the fracture surface of the composite specimens tested at three temperatures are shown in Fig. 5. The residual stress shows an initial increase with distance from fracture surface, then decreases. Also, the residual stress decreases with increasing testing temperature.

4. Micrographic studies

Figures 6 and 7 show SEM fractographs of the speci-

mens tested at 373 and 473 K with a loading velocities of 10^{-2} and $10 \text{ m} \cdot \text{s}^{-1}$, respectively. Evidence of whisker pull-out and dimples can be clearly noticed in these figures, even though at the macroscopic level the material exhibits essentially brittle behavior. These SEM observations reveal no significant differences in failure mechanisms with those at room temperature.

IV. Discussion

1. Effect of loading velocity at elevated temperature

As stated in the previous study⁽¹¹⁾, the effect of the loading velocity on the fracture toughness can be modified by assuming the existence of an incubation time⁽¹⁷⁾. According to the incubation time theory, it can be inferred that for the same reason the fracture toughness increases with increasing loading velocity at elevated temperatures (see Figs. 3 and 4). However, it must be noticed that the increase in magnitude of the fracture toughness with increasing loading velocity is reduced at elevated temperatures, although the time to maximum loading point still increased with increasing loading velocity and testing temperature (see Fig. 8). This can be attributed to the decrease in the Young's modulus and stress concentration between the reinforcements of SiC whiskers and the matrix, when the tests were carried out at elevated temperatures. Compared to data on room temperature, Young's modulus of the present material decreases by about 12% at the testing temperatures up to 473 K⁽¹⁸⁾. Also, this can be seen from the load-deflection curves as shown in Fig. 2, in which the slope of the curve decreases with increasing testing temperature. Meanwhile, the incubation time depends on the Young's modulus of the testing material, and the shorter the incubation time, the smaller is the difference of fracture toughness caused by changes in loading velocity⁽¹⁹⁾. In other words, since Young's modulus decreases with temperature, the incubation time becomes shorter and decreases the influence of the loading velocity on fracture toughness. In fact, the stress concentration between the

Fig. 3 The effect of testing temperature on the fracture toughness with different loading velocities.

Fig. 4 The relationship between fracture toughness and stress intensity rate of the composite at different temperatures.

Fig. 5 Residual stress distribution near fracture surface with a loading velocity of $10 \text{ m} \cdot \text{s}^{-1}$, at different temperatures.

Fig. 6 SEM fractographs after fracture toughness test with a loading velocity of (a) and (b) $10^{-2} \text{ m} \cdot \text{s}^{-1}$, (c) $10 \text{ m} \cdot \text{s}^{-1}$ at 373 K. The black and white arrows indicate pull-out whiskers and microvoids or microcrack, and “P”, “W” as well as “T” labels indicate the dimple, the whisker and tear ridge, respectively.

SiC whiskers and the matrix of the aluminum alloy is reduced. Thus, the sensitivity of testing material on the loading velocity is also reduced at elevated temperatures.

2. Effect of the testing temperature

The strength dependence on testing temperature for a variety of metals and alloys has been well characterized. For the materials, as the testing temperature is increased, there is a decrease in fracture toughness with reducing strength as well as modulus. This is usually called “softening”. The same sensitivity in terms of softening was also observed in the present composite. It was found that the tensile strength was reduced from 475 to 364 MPa when the testing temperature rose from room temperature to 473 K⁽¹⁸⁾. Moreover, from Fig. 2, it is evident that when the testing temperature increased there is still nearly pure elastic fracture at the maximum load. Fur-

Fig. 7 SEM fractographs after fracture toughness test with a loading velocity of (a) and (b) $10^{-2} \text{ m} \cdot \text{s}^{-1}$, (c) $10 \text{ m} \cdot \text{s}^{-1}$ at 473 K. The arrows and labels indicate the same mean with in the Fig. 6.

Fig. 8 The influence of loading velocity on the time to maximum loading point at different temperatures.

thermore, within the range of the present testing temperature, there is no significant change in the mode of temperature-dependent fracture. Therefore, the fracture

toughness of the composite decreased when the testing temperature was increased.

Generally, from the viewpoint of temperature dependence of the dynamic elastic modulus, it has been demonstrated that the dynamic elastic modulus of aluminum matrix composite materials decrease as the testing temperature (T_t) increases, and this can be attributed largely to the matrix⁽²⁰⁾. This is logical from the two points of view: first, the composite material consists of nearly 80% aluminum matrix, and second, there is a correlation among the melting point T_m , the modulus and the interatomic forces in materials, making the decrease in modulus high for aluminum the matrix (at 473 K, $T_t/T_m \approx 0.55$) and low for SiC (at 473 K, $T_t/T_m \approx 0.2$). The similar behavior was observed in $\text{Al}_2\text{O}_3/\text{A6061}$ composite⁽²¹⁾. More specifically, experimental and numerical studies of aluminum and the aluminum alloy reinforced with whisker⁽²²⁾⁽²³⁾ have indicated that the flow stress due to hot deformation reduced when the deforming temperature is increased, especially with a high strain rate.

On other hand, the residual stress results shown in Fig. 5 suggests a decrease in residual stress with increasing testing temperature. This residual stress represents the amount of damage caused by a strong stress wave near the main crack (or the fracture surface)⁽²⁴⁾⁽²⁵⁾. The residual stress in the composite material decreases with increasing testing temperature. From the loading-deflection curves shown in Fig. 2, it is apparent that for the present materials, the maximum loading decreases, while

the deflection show no large change when the testing temperature increases. This result is consistent with that for the residual stress. It seems that the range of the damage zone mainly depends on loading velocity, whereas, the amount of damage in this zone depends on both loading velocity and temperature.

3. Fracture behavior

In all the cases, from room temperature to 473 K, the fracture surfaces showed ductile dimples, signs of void formation and a few of tear ridges (see Figs. 6 and 7). The dimples and voids are related to whisker pull-out and whisker breaking. These seems to be no evident change of the fracture mechanism compared to that at room temperature. However, the proportions of whisker breakage and pull-out, as well as the extent of matrix deformation, varied with temperature.

As shown in Figs. 6 and 7, microcracks are clearly visible, but, the amount of microcracking and microvoids at high temperature are less than at low temperature. Just, it was found in the previous study that microvoids and microcracks are mainly initiated by the cracking whiskers and interface debonding, which are connected with inclusion and clustered whisker areas. Because of the various mechanisms of void initiation, such as the volume fraction of void-nucleation whisker and local whisker clusters, the voids can grew to various sizes. This is demonstrated in Fig. 9. From this figure, it is evident that the dimples become shallower with increasing testing temperature, while the size of the dimples

Fig. 9 SEM fractographs of fracture surfaces after fracture toughness test with a loading velocity of (a) and (c) $10^{-2} \text{ m} \cdot \text{s}^{-1}$, (b) and (d) $10 \text{ m} \cdot \text{s}^{-1}$ at (a) and (b) 373 K, (c) and (d) 473 K, showing the dimples size and depth with different testing conditions. The black and white arrows indicate pull-out whiskers or the traces after pull-out and microcracks, respectively.

Fig. 10 Crack path morphologies for precracked specimen with loading velocity of $10 \text{ m} \cdot \text{s}^{-1}$, at: (a) 373 K, and (b) 474 K, respectively.

increases.

Microvoiding and microcracking occurred within a wide range from the fracture surface at high loading velocity, which indicates that the local microvoids and microcracks might not have enough time to join together to form a major crack, and the growth rate of microcracks appear to be lower than that of the major crack which causes final failure. Before a catastrophic failure, the composite specimen has experienced a high extent of microcracking, microvoiding and matrix plastic deformation. However, when the testing temperature increased to 473 K, since both the strength and Young's modulus of the testing material decreased, as well as the stress concentration between the reinforcement of SiC whiskers and the matrix, the fracture surfaces at such a temperature (Fig. 10(b)) are less uneven than that at low temperature (Fig. 10(a)). Nevertheless, as shown in Fig. 9, the void-growth stage of the microcracking process was limited at low temperature compared to that at high temperature. The dimple size was bigger at high temperature than at low temperature, and the number of whisker breakers decreases with increasing testing temperature.

V. Conclusions

An experimental study has been conducted at elevated temperature to investigate the effects of loading velocity on the fracture behavior of a metal-matrix composite, 6061-T6 aluminum reinforced with silicon carbide whiskers. The main results can be summarized as follows.

1. The variation in fracture toughness of a SiCw/6061 aluminum alloy composite at elevated temperatures with different loading velocities is smaller to that at room temperature. However, the influence of loading velocity on the fracture toughness is less.

2. The fracture toughness of the composite decreases

as the testing temperature increases with different loading velocity. This is considered to be associated with a decrease of both the strength and Young's modulus, as well as the reduction of stress concentration between the SiC whisker reinforcements and the matrix.

3. SEM fractography results indicate that the fracture surface becomes less uneven, and matrix dimples become shallower, but bigger, and the amount of the damage decreases with increasing testing temperature.

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