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Abstract

Evaluation of fracture toughness of short fiber reinforced metal matrix composites (MMCs) becomes important for their application as structural materials. Therefore, in this study static and dynamic fracture toughness of MMCs manufactured by squeeze casting process were investigated. A number of MMCs were tested with various matrix alloy, volume fractions and specifically types of reinforcements. It was found that static and dynamic fracture toughness of MMCs was remarkably decreased by the addition of ceramic reinforcements. Compared with static fracture toughness, the mean cause of the decrease difference of dynamic fracture toughness and notch dynamic fracture toughness is due to the effect of dynamic velocity under impact loading. The toughness of ceramic reinforced MMCs is controlled by a complex interaction between the matrix alloy and reinforcement. Important properties which influence toughness include the type of reinforcement (appearance, size), volume fraction and combination of reinforcement and the matrix alloy. Notch fracture toughness of MMCs for simple evaluation was also discussed.

Keywords

Fracture toughness, notch fracture toughness, metal matrix composites, squeeze infiltration method

1. Introduction

Recently, there has been an effort to use discontinuously reinforced metal matrix composites for engineering structural applications. These composites can offer distinct technological advantages over continuously reinforced MMCs, including fabricability using a squeeze infiltration method, as well as cost advantages [1–5].

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Many studies on metal matrix composites (MMCs) have been done but there have been very limited structural applications so far since significant problems remain unresolved, such as complexity of processing, high costs, low fracture toughness and low strain to failure [6–8].

Many studies have been undertaken concerning the static fracture toughness (K_{1c}) of aluminum alloys with either SiC particulate or whisker reinforcement. Few studies on comparison between the static and dynamic fracture toughness behavior are available in the literature. These have been done mainly on the fracture toughness of discontinuous MMCs reinforced by the addition of a single reinforcement, such as Al_2O_3, SiC, carbon, etc. [9–13]. However, little attention was paid to the effect of hybrid metal matrix composites on fracture toughness behavior. Moreover, reinforcement with a single fiber has been the major subject of research and development, while reinforcement with hybrid fibers that consist of two or more reinforcements has not widely been studied. Evaluation of fracture toughness of short fiber reinforced metal matrix composites becomes important for application as structural materials [10–15].

In this work, therefore, the authors conducted an experimental study to investigate the fracture toughness behavior of hybrid MMCs, and also to compare the behavior of static and dynamic fracture toughness. In addition, the plane strain and notch fracture toughness for MMCs were evaluated to find the effect of notch at the crack tip.

2. Experimental Procedure

2.1. Materials and Fabrication

For the fabrication of composite materials, various reinforcements such as alumina, SiC whisker and carbon fiber were used. Typical specifications of reinforcements used are listed in Table 1. The cast Al alloy of AC2B, AC8A, and Al6061 wrought product were used as matrix materials. The chemical compositions of the matrix materials are shown in Table 2 and the mechanical properties are shown in Table 3 [9, 16–18].

After preparation of preform by vacuum equipment, we have fabricated the MMCs by squeeze infiltration method. Casting ingots for mechanical and fracture toughness tests were given a T6 heat treatment as indicated in Table 3.

2.2. Mechanical and Fracture Toughness Tests

Room temperature tensile tests were performed with a universal testing machine. Tensile tests were displacement controlled and the displacement rate was 0.5 mm/min. To measure strains, an extensometer with a gage length of 12.5 mm was attached in the center of the gage length to round bar specimen. Round tensile specimens with 6.5 mm diameter and 65 mm length were machined in the perpendicular direction of the applied pressure.

Table 1.
Specification of various reinforcements used

Material	Den. (g/cm^3)	Diameter (mm)	Length (mm)	Aspect ratio (1/d)	T.S. (GPa)	*E* (GPa)
Al_2O_3	3.3	3	150	50	2.0	310
SiC_w	3.2	0.45	15	33.3	5.0	600
C_{Pan}	1.9	9.08	119	13.1	2.0	280

Table 2.
Specification of various matrices used

Material	Chemical composition (%)									
	Si	Cu	Mg	Ni	Fe	Mn	Zn	Ti	Pb	Al
AC2B	6.0	3.0	0.4	0.3	0.9	0.4	0.09	0.1	0.15	Rem.
AC8A	12.7	1.1	0.9	1.57	0.8	0.1	0.12	0.15	0.04	Rem.
Al6061	6.0	0.2	1.0	–	0.6	0.1	0.2	0.1	–	Rem.

Table 3.
Mechanical properties and heat treatment conditions of various Al alloys

Material	Mechanical property			T6 heat treatment	
	T.S. (MPa)	Y.S. (MPa)	Elong. (%)	Solution	Precipitation
AC2B	254	–	>5	500°C for 10 h	160°C for 8 h
AC8A	275	–	<1	510°C for 4 h	170°C for 7 h
Al6061	310	275	10	540°C for 10 h	180°C for 8 h

The static fracture toughness test was carried out at room temperature according to ASTM E399 using a hydraulic testing machine having 5 ton capacity. In the case of matrix alloy, we performed the CTS test using the single specimen J-integral test method according to ASTM standard E813. The dynamic fracture toughness (K_{1d}) test was carried out at room temperature and a 300 J capacity instrumented Charpy impact testing machine was used. The fatigue tests for the induced pre-crack were conducted under constant load amplitude with an R value of 0.1 using a sinusoidal wave form at a frequency of 10 Hz. Crack length measurements were performed using a traveling light microscope (with resolution < 5 mm) on the surface of the specimens.

Using P_Q and P_m obtained from experiment, static and dynamic fracture toughness were calculated using equations (1) and (2), respectively.

$$K_Q = P_Q/BW^{1/2} \cdot Y(a/W), \tag{1}$$

where P_Q is 5% offset of maximum load, B and W are thickness and width of specimen, respectively, and $Y(a/W)$ is configuration coefficient of CT specimen.

$$K_{1d} = P_m \cdot S/BW^{3/2} \cdot Y(a/W), \tag{2}$$

where P_m is maximum load after impact loading, and S is span of specimen, $Y(a/W)$ is configuration coefficient of 3-point bending specimen.

Test specimens were machined from cast ingots parallel to the applied pressure direction as shown in Fig. 1(a). The static fracture toughness tests were performed

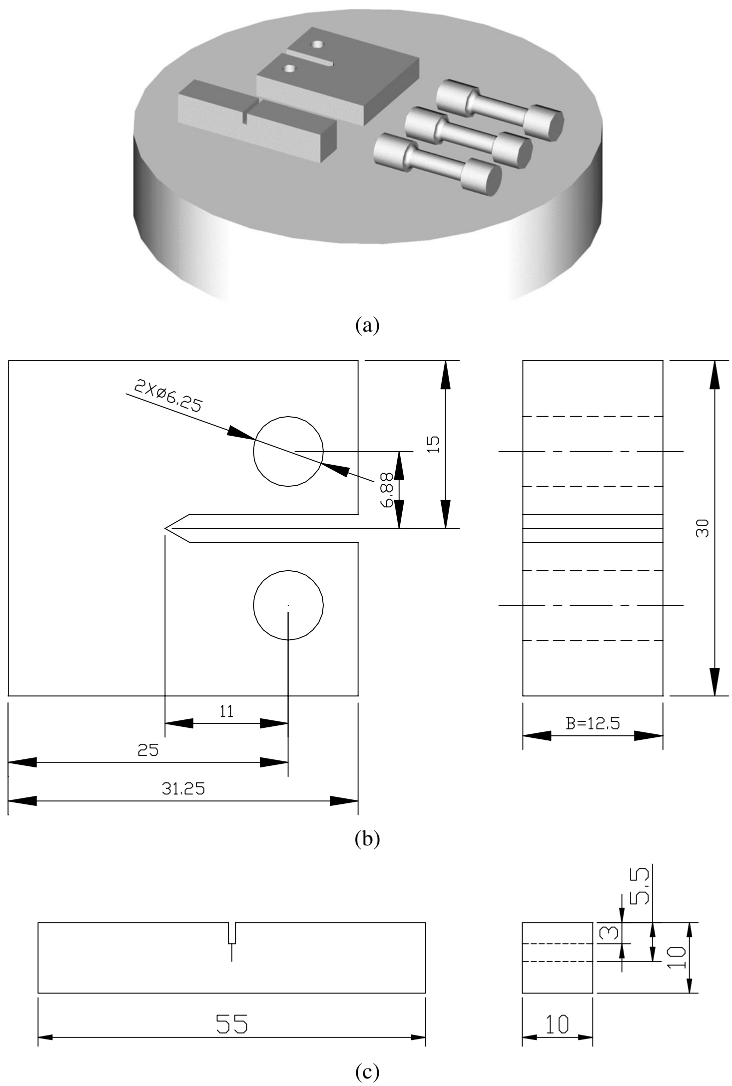


Figure 1. Orientation from cast ingot and dimension of fracture toughness test specimen. (a) Specimen orientation from cast ingot; (b) static fracture toughness test specimen; (c) dynamic fracture toughness test specimen.

on compact tension (CT) type specimens of 25 mm width and 12.5 mm thickness as shown in Fig. 1(b) and the dynamic fracture toughness tests were performed on 3-point bending type specimens of 55 mm width and 10 mm thickness.

3. Results and Discussion

3.1. Static Fracture Toughness

The various manufacturing methods of composites currently in use dictate that large microstructural variations between different materials are to be expected. This means that fracture toughness behavior of MMCs might be sensitive to actual manufacturing methods, such as the squeeze casting and powder metallurgy route. Fracture toughness behavior of MMCs is associated not only with the matrix, but is also affected by some other factors, such as type, size and volume fraction of reinforcement. Therefore, we have focused on the effects of controlling the complex interaction between the matrix alloy and reinforcement on fracture toughness of short fiber reinforced MMCs.

Table 4 summarizes the results of the static and dynamic fracture toughness experiments. We have discussed this with respect to three types of metal matrix composites in which a different matrix alloy is used as follows. In the case of AC2B based MMCs, Fig. 2(a) shows that K_{1c} value of alumina and hybrid composites was decreased about 40% compared with that of matrix alloy. Furthermore, from Table 4, we found that the K_{1c} values of Al_2O_3-15%/Al and Al_2O_3-12%/C-3%/Al decreased by 36.3% and 34.7%, respectively, with the same matrix material of AC2B. However, ductility of MMCs decreases remarkably since ceramic re-

Table 4.
Results of fracture toughness for various composites

Materials	Fracture toughness (MPa$\sqrt{m}$)			
	K_{1c}	$K_{1c,N}$	K_{1d}	$K_{1d,N}$
AC2B	26.2	–	31.1	–
Al_2O_3-15%/Al	16.7	–	18.8	–
Al_2O_3-12%/C-3%/Al	–	17.1	–	19.5
Al_2O_3-20%/Al	15.3	–	16.3	–
AC8A	–	19.4	–	21.1
Al_2O_3-15%/Al	–	14.1	–	16.8
Al_2O_3-20%/Al	–	12.1	–	14.2
Al6061	29.5	–	35.4	–
Al_2O_3-15%/Al	17.8	–	26.5	–
Al_2O_3-15%(N)/Al	–	19.5	–	27.0
Al_2O_3-10%/SiC_w-5%/Al	15.3	–	23.7	–
Al_2O_3-10%/SiC_w-5%/(N)/Al	–	17.6	–	22.6
Al_2O_3-20%/Al	14.2	–	18.4	–

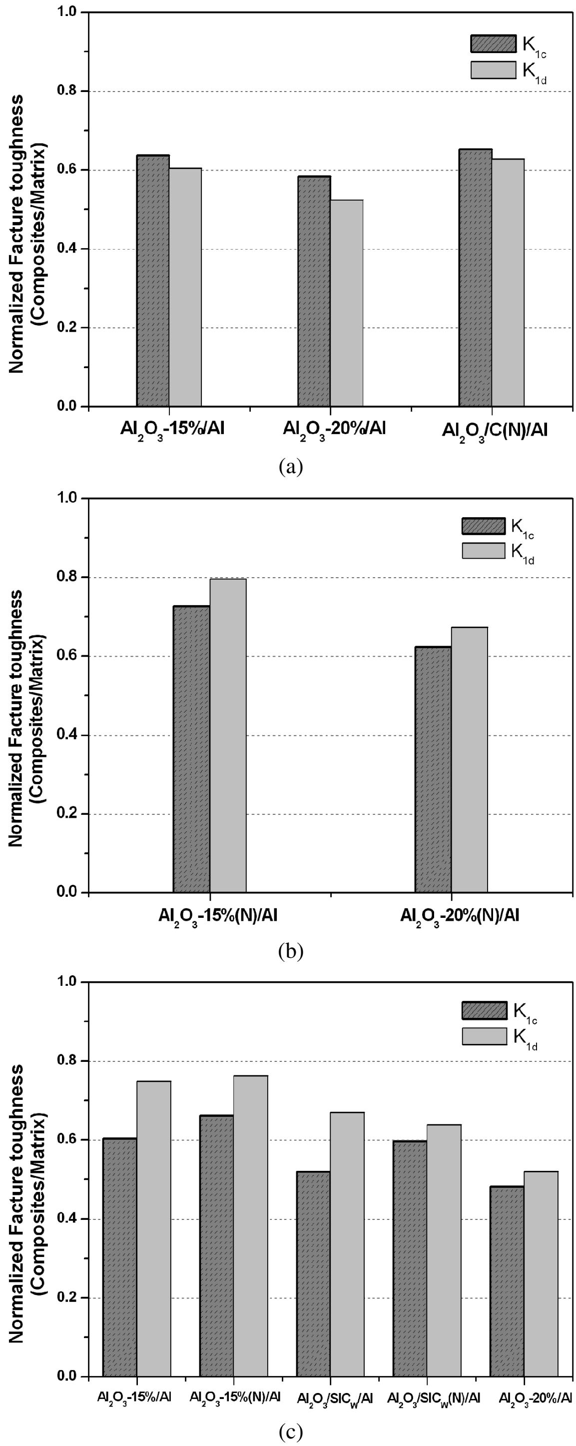


Figure 2. Composites in comparison with (a) AC2B, (b) AC8A and (c) Al6061.

Table 5.
Elongation properties of the AC2B based MMCs

Composite	Al_2O_3-15%/Al	Al_2O_3-12%/C-3%/Al	Al_2O_3-20%/Al
Elongation (%)	3.5	3.6	3.3

inforcements in composites restrain the deformation of a matrix alloy. The K_{1c} value of Al_2O_3/C/Al composite showed little greater than that of Al_2O_3/Al composite. We also found that the elongation of Al_2O_3/C/Al composite was improved over Al_2O_3/Al composite as shown in Table 5 due to the effects of hybrid reinforcements. The ductility of alumina composite was decreased with the increase of volume fraction, so that elongation of Al_2O_3-20%/Al composite was decreased up to 5.7% compared with that of Al_2O_3-15%/Al composite. Consequently, reduction of ductility in composites resulted in the deterioration of fracture toughness.

In the case of AC8A based MMCs, Fig. 2(b) shows that the static fracture toughness test was performed with a notch specimen, since it was very hard to produce the fatigued pre-crack in AC8A matrix alloy with elongation of 0.3%. Therefore, strictly speaking, fracture toughness of AC8A based MMCs must be defined as notch fracture toughness ($K_{1c,N}$) rather than K_{1c}. The $K_{1c,N}$ values of Al_2O_3-15%/Al and Al_2O_3-20%/Al composites decreased up to 27.3% and 37.6%, respectively, compared with that of AC8A alloy which was used as the matrix material of the composites. AC8A based MMCs, however, showed less reduction rate than AC8A and Al6061 based MMCs. These results originate from the character of the AC8A alloy, which has a low strain to failure. This implies that AC8A aluminum alloy is not appropriate for structural materials. With comparable amounts of fibers, the fracture toughness of Al_2O_3-20%/Al composites were decreased by 14.2% over that of Al_2O_3-15%/Al composites. The increase of volume fraction in MMCs indicated the decrease of fracture toughness was caused by a low ductility.

The studies on Al 6061 based MMCs deal with three effects — the nature of the hybrid, the volume fraction and the presence of a notch — on their fracture toughness. As shown in Fig. 2(c), K_{1c} values for Al_2O_3-15%/Al and Al_2O_3-20%/Al composites were remarkably decreased compared with that of matrix alloy, and the K_{1c} value of Al_2O_3-20%/Al composites was decreased by 8.4% over that of Al_2O_3-15%/Al composites with the increase of volume fraction. Figure 2(c) shows that the K_{1c} value of Al_2O_3%/SiC_w%/Al hybrid composites was shown to be 14.0% lower than that of Al_2O_3-15%/Al composites. Consequently, an Al_2O_3/SiC_w/Al composite appears to be more effective in strength than Al_2O_3/Al composites [5, 6, 8, 9]. Fracture surfaces of Al_2O_3/SiC_w/Al composites show a different type from those of Al_2O_3/Al composites. This fineness of microstructure in Al_2O_3/SiC_w/Al composites is more effective in strengthening than in Al_2O_3/Al composites. On the other hand, the values of $K_{1c,N}$ of Al_2O_3-15%/Al and Al_2O_3/SiC_w/Al composites were found to be 9.6% and 15.0% greater than those of K_{1c} which is produced

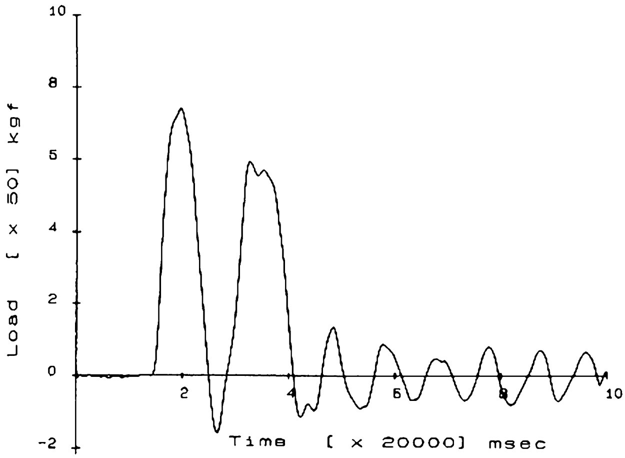


Figure 3. Typical plot of relations between load and time for Al_2O_3/Al composites.

when pre-cracked at the crack tip notch. Therefore, notch fracture toughness should be increased at least around 9.6–15.0% over plane strain fracture toughness.

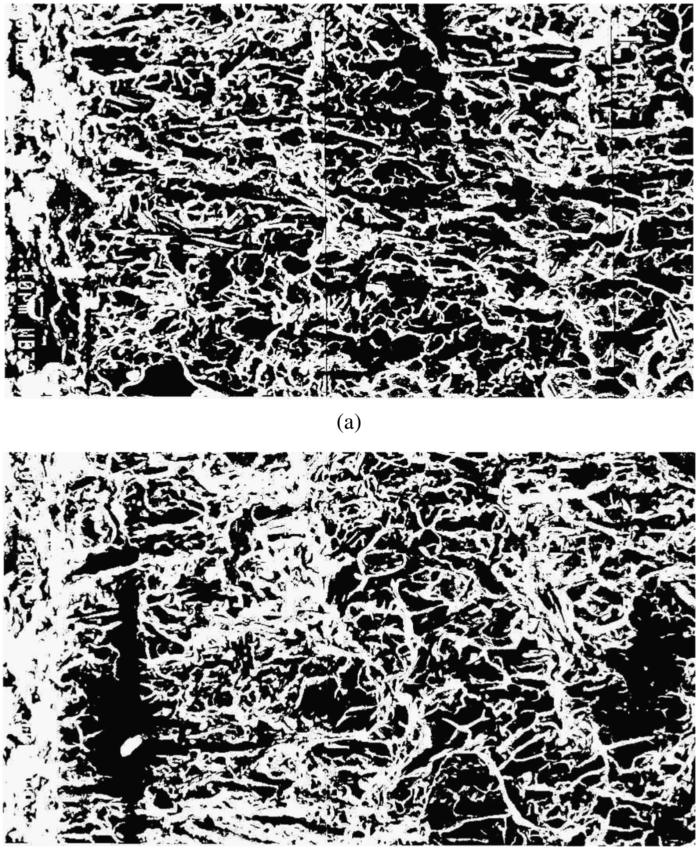
In consequence, it can be shown that static fracture toughness of MMCs is closely related with the ductility of material itself, as well as volume fraction, types of reinforcements and matrix alloy. This effect is associated with the more extensive matrix regions surrounding the larger diameter reinforcements, which enhance the toughness by producing additional constraint on the fracture event through matrix plastic deformation. Our results showed similar behavior to that described by Flom and Arsenault [10]. They reported that crack initiation fracture toughness did not depend on SiC particle size and crack growth fracture toughness increased as the size of the SiC particle increased. Notch fracture toughness values are shown to be within 10% of the plane strain fracture toughness. Our results agree with Crowe *et al.*'s results [11] which reported that the apparent fracture toughness fits the relation $K_{1c}(\rho) = K_{1c}(1 + \rho/2c)^{3/2}/(1 + \rho/c)$.

Figure 3 shows a typical plot of relations between dynamic load and time after impact tests, in which the computer aided instrumented Charpy impact testing (CAI) system, is used. From P_m of this graph and equation (2), we calculated the value of K_{1d}.

3.2. Dynamic Fracture Toughness

The fracture toughness must be evaluated under the dynamic loading condition, when the materials are used for structures such as a pressure vessel that are desired to have a higher safety and take account of the dynamic loading effect. Dynamic fracture toughness may also be needed to give information relevant to the use of discontinuously reinforced metal matrix composites for engineering structural applications.

In the case of AC2B based composite systems, Fig. 2(a) shows that K_{1d} values of Al_2O_3-15%/Al and Al_2O_3/C/Al composites were decreased about 40% compared



(a)

(b)

Figure 4. SEM photographs of (a) Al_2O_3/Al and (b) Al_2O_3/C/Al composites.

with that of matrix alloy. The K_{1d} value of Al_2O_3/C/Al hybrid composites improves by 3.7% over that of Al_2O_3-15%/Al composites. These results are well reflected in elongation of carbon hybrid composite, which is more effective in toughening than only alumina composites. The effect of carbon fibers on the fracture toughness characteristics in the Al_2O_3/C/Al composites, however, appears slightly improved.

Figure 4 shows the SEM photographs of (a) Al_2O_3-15%/Al and (b) Al_2O_3/C/Al composites near the crack tip after impact loading. The fracture surface morphology of Al matrix appears widely dimpled, also called, ductile fracture. The fracture surface morphologies of both Al_2O_3-15%/Al and Al_2O_3/C/Al composites appear to be similar. Specifically, the surface morphologies of Al_2O_3/C/Al composites are far less rough, since Al_2O_3-15%/Al composites do not contain carbon fibers. Overall, the dimple size of the fracture surfaces in the hybrid composite appeared much smaller than that of Al_2O_3-15%/Al composites. However, the dimple size of matrix clearly increases with increase of fiber size. This dimple pattern could be affect on the fracture toughness for each material.

Considering the notch fracture toughness, in the case of AC8A based MMCs, Fig. 2(b) shows that $K_{1d,N}$ of Al_2O_3/Al composites was decreased about 20–30% over matrix alloy. $K_{1d,N}$ of alumina composites was decreased with the increase of volume fraction due to a low ductility. The hybrid effect of Al_2O_3/SiC_w/Al composites on the dynamic fracture toughness resulted in the decrease of 16.3% than that of Al_2O_3-15%/Al composites. The difference between pre-cracked K_{1d} and $K_{1d,N}$ of Al_2O_3/Al composites is smaller than those of static fracture toughness. Consequently, it means that dynamic fracture toughness behavior is affected by loading velocity under impact loading.

Figure 5 shows comparison between static and dynamic fracture toughness for both (a) AC8A and (b) Al6061 based composites. As shown in Fig. 5(a), the sta-

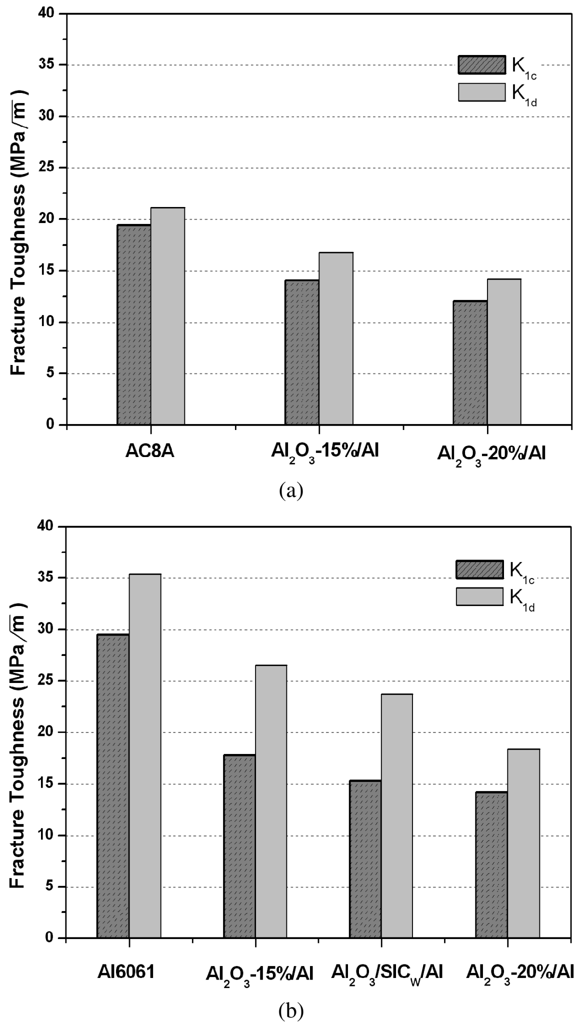


Figure 5. Static and dynamic fracture toughness for both (a) AC8A and (b) Al6061 based composites.

tic fracture toughness of AC8A matrix and composites under quasi static loading rate of 1.23 $\text{MPa}\sqrt{\text{m}}$/s decreases about 10% over those of the dynamic fracture toughness under fast loading rate of 5×10^6 $\text{MPa}\sqrt{\text{m}}$/s. The results are also consistent with showing a rather large increase in fracture toughness accompanying higher loading rates. On the basis of Duffy and co-workers' model [13], it can be described that the increase in fracture toughness at the higher rates is due to a combination of an increase in the yield strength and fracture strain at the higher rates. The dynamic fracture toughness of an alumina reinforced aluminum alloy is found to decrease as the volume fraction of alumina increase. As shown in Fig. 5(b), K_{1c} and K_{1d} values show a large difference as the ductility of matrix alloy increase.

From these results, static and dynamic fracture toughness behavior of MMCs are associated not only with the matrix, but also affected by some other factors, such as type, size and volume fraction of reinforcement. In addition, the fracture toughness of ceramic reinforced MMCs is controlled by a complex interaction between the matrix alloy and reinforcement. No single parameter appears to be capable of describing the full toughness response of MMCs.

The poor toughness of MMCs derives from low initiation energy for fracture as a result of their high elastic modulus and low failure strains and low propagation energy. Also, it is important to choose fibers of reinforcements for the development of hybrid metal matrix composites whether the effects of hybrid reinforcement always improve all of their engineering properties or not. Moreover, it is possible to improve the fracture toughness of these MMCs by the use of higher failure strain reinforcements and by increasing the propagation energy by the introduction of additional energy absorbing mechanisms such as pull-out and reinforcement and matrix debonding.

4. Conclusions

In this study, the characterizations of static and dynamic fracture toughness behavior in various metal matrix composites were evaluated. These results can be summarized as follows.

The static fracture toughness of MMCs is found to decrease as the volume fraction of alumina increases. Reduction of ductility in composites resulted in the deterioration of fracture toughness. The K_{1c} value of Al_2O_3/C/Al hybrid composites slightly improves over that of Al_2O_3/Al composites. The $K_{1c,N}$ value of MMCs was increased about up to 10% over that of K_{1c}. The major effects which influence toughness could be found the type of reinforcement, volume fraction and combination of reinforcement and the matrix alloy.

The dynamic fracture toughness (K_{1d}) of MMCs is found to decrease as the volume fraction of alumina increases. Static and dynamic fracture toughness of MMCs remarkably decreased due to a low strain to failure. K_{1c} and K_{1d} values of MMCs show a big difference whether the matrix alloy is ductile. The effect of carbon fibers on the fracture toughness characteristics in the Al_2O_3/C/Al composites appears slightly improved. Specifically, dynamic fracture toughness of MMCs was slightly increased compared with that of static fracture toughness because of the dynamic loading effect. Notch dynamic fracture toughness ($K_{1d,N}$) of MMCs was found to be insensitive to actual loading speed.

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