Continuum Damage Modeling for Dynamic Fracture Toughness of Metal Matrix Composites*

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Abstract
Short fiber reinforced metal-matrix composites (MMCs) have widely adopted as structural materials and many experimental researches have been performed to study fracture toughness of it. Fracture toughness is often referred as the plane strain (maximum constraint) fracture toughness $K_{IC}$ determined by the well-established standard test method, such as ASTM E399. But the application for dynamic fracture toughness $K_{ID}$ has not been popular yet, because of reliance in capturing the crack propagating time. This paper deals with dynamic fracture toughness testing and simulation using finite element method to evaluate fracture behaviors of MMCs manufactured by squeeze casting process when material combination is varied with the type of reinforcement (appearance, size), volume fraction and combination of reinforcements, and the matrix alloy. The instrumented Charpy impact test was used for $K_{ID}$ determination and continuum damage model embedded in commercial FE program is used to investigate the dynamic fracture toughness with the influence of elasto-visco-plastic constitutive relation of quasi-brittle fracture that is typical examples of ceramics and some fibre reinforced composites. With Compared results between experimental method and FE simulation, the determination process for $K_{ID}$ is presented. FE simulation coupled with continuum damage model is emphasized single shot simulation can predict the dynamic fracture toughness, $K_{ID}$ and real time evolution of that directly.

Key words: Static and Dynamic Fracture Toughness, Continuum Damage Mechanics, Metal-Matrix Composites, Reinforcements, Volume Fraction, Aluminum Matrix Composites, Finite Element Method, Charpy Impact Test

1. Introduction
Discontinuously reinforced metal matrix composites have widely adopted as structural materials for aerospace, automotive, electronic, boutique sport industries due to their high specific strength, stiffness, improved wear and lubrication with thermal resistance. Matrix and Discontinuous reinforcement such as whisker, short fiber, particles are selective combination for specific applications of material design. Manufacturing and fabrication method is also important parameter to maximize material characteristic of each applications. The most commonly used process is squeeze infiltration method. Selectively reinforced MMC pistons using this squeeze infiltration method introduced by Toyota Motor Manufacturing in 1983 as the first commercial MMC application. Honda Prelude used this MMC liners providing improved wear resistance to allow reduced liner thickness and its
higher thermal conductivity gives lower operating temperature extending engine life. Application of MMCs being increased, data concerning mechanical properties of MMC are not sufficiently clarifies in special dynamic fracture toughness $K_{\text{id}}$ which might be more practical use as to real service loads. Many studies have been undertaken about $K_{\text{id}}$ of aluminum alloy with either SiC particulate or whisker reinforced, and single reinforcement such as Al$_2$O$_3$, SiC, and C, etc [6,8-14]. Hybrid fibers of two or more reinforcements has not been widely studied.

At the dynamic toughness study, G. Weisbrod and D. Rittel [16] developed hybrid experimental-numerical calculation method of $K_{\text{id}}$ that combines experimental load time history and numerical crack opening displacement measurement. Bui et al. [17], studied the dynamic effects carrying over the potential of force and displacements history before crack starts to propagate. Isamu Yamamoto et al. [18] studied micro- and macro deformation features at the different loading rate to understand the loading rate dependence of the fracture energy. G. P. Cammarota et al. [19] suggest that the instrumented Charpy impact test is not always representative of LEFM conditions and corrective factor as the nucleation energy and propagation energy ratio is used to take into account of the plastic deformation at the determination of $K_{\text{id}}$.

In this study, the authors conducted the experimental study to investigate the dynamic fracture toughness behavior of hybrid MMCs and followed FE simulation using continuum damage model to identify fracture toughness coupled elasto-Visco-plastic relation during the dynamic failure. Continuum damage modeling was newly adopted to the challenge of fracture time prediction of MMCs which was issue relies on experimental methods, e.g. crack tip monitoring using high speed camera, single wire fracture gages, strain gages, and/or computer assisted fracture detection, since the onset of the crack propagation (fracture time) determines $K_{\text{id}}$ directly. To estimate the potential for crack starts at the high speed loading, continuum damage modeling which is coupled with viscoplastic and anisotropy model was used for damage threshold and damage evolution. Being compared experimental $K_{\text{id}}$ from instrumented Charpy impact test and FE based $K_{\text{id}}$ by convolution integral method suggested by G. Weisbrod, the damage modeling is deeply discussed the feasibility for fracture mechanisms of critical dynamic toughness $K_{\text{id}}$ in this paper.

2. Continuum Damage Mechanics Model

Quasi-brittle fracture presents the fracture processes which are not accompanied by large-scale plastic flow, but take a dissipation energy prior to cracking exists. This type of fracture may have some reversible sliding of nano- or microcracks considered as initial defects. Fracturing has a process of nucleation, growth and coalescence of microscopic defects and at the end a macroscopic crack. MMCs also exhibits typical quasi-brittle fracture process with toughening mechanism as crack bridging, fiber pullout and crack deflection[21]. The fracture process is presented with progress of damage concerning both reinforcement cracking and matrix failure for different volume fractions of locally damaged material model at micro level.

Volume defects of micro cavities or micro cracks are represented with damage variable physically defined by the surface density of micro cracks or intersected micro void density lying on the cutting plane of the RVE (Representative Volume Element).

The schematic picture is shown at Fig.1[22] and damage variable is defined as the below equation (1).

$$D_{(a)} = \frac{\partial S_D}{\partial S}$$

(Introducing effective stress concept, damage represents the mathematical stress changes as the effective stress tensor for multiaxial case (Lemaitre and Chaboche, 1990)

$$\bar{\sigma}_{ij} = \sigma_{ij} (I-D)_{kij}^{-1}$$
Fig. 1. Mathematical continuous damage definition

To describe the coupled state potential of the material, the state potential of the material is the function of all the state variable with the Helmholtz specific free energy equation written as $\psi(\varepsilon, D_{ij}, \alpha, \sigma, T)$.

Gibbs specific free enthalpy $(\psi^*)$ deduced from Helmholtz function and finally expressed as

$$
\psi^* = \psi_e^* + \frac{1}{\rho} \sigma_{ij} \varepsilon_{ij}^p - \psi_p - \psi_T
$$

Where $\psi_e^*, \psi_p, \psi_T$ is elastic contribution, plastic hardening, thermal contribution only.

By the derivatives, the associated variables are defined as follows:

$$
R = -\rho \frac{\partial \psi^*}{\partial r}, \quad X_{ij} = -\rho \frac{\partial \psi^*}{\partial \alpha_{ij}}, \quad -Y_{ij} = -\rho \frac{\partial \psi^*}{\partial D_{ij}}
$$

The energy density release rate($Y_{ij}$) is also derived from the state potential and written as function of the effective elastic energy density:

$$
Y_{ij} = \frac{1}{2} E_{ijkl} \varepsilon_{ij}^l \varepsilon_{kl}^j = \frac{1}{2} \tilde{\sigma}_{ij} \tilde{\varepsilon}_{ij} = \frac{\tilde{\sigma}_{eq}^2 \tilde{R}_v}{2E}, \quad \tilde{R}_v = \frac{2}{3} (1 + \nu) + 3(1 - 2\nu) \left( \frac{\tilde{\sigma}_H}{\tilde{\sigma}_{eq}} \right)^2
$$

We call $R_v$ as the effective triaxiality function and

$$
\tilde{\sigma}_{eq} = (H\sigma^D H)_{eq} = \left[ \frac{3}{2} (H\sigma^D H)^D_{ij} (H\sigma^D H)^D_{ij} \right]^{1/2}, \quad \tilde{\sigma}_H = \frac{\sigma_H}{1 - \eta D_H}
$$

Many experimental results shows the dissipative damage potential function $F_D$ is primarily a function of $Y$.

$$
F_D = \frac{S}{(s + 1)(1 - D)} \left( \frac{Y}{S} \right)^{s + 1}
$$

where $S$ and $s$ are material parameters.

The evolution equation for the damage variable is defined as:

$$
\dot{D} = \left( \frac{Y}{S(1 - D)} \right)^s \dot{p}
$$

If $p > p_D$, Damage is evolved to go mesocrack initiation, where $p_D$ is the damage threshold.

To implement this damage model for finite element method in this study, general power law of material model or piecewise stress strain curve is used in coupling with this damage law by function of plastic strain and strain rate.
3. Determination of $K_{id}$

The dynamic fracture toughness is fully accounted with evolution of $K_{id}(t)$ and $K_{id}^{COD}$ at the onset of crack propagation as a key property under dynamic loading. Being used the instrumented Charpy impact testing machine and single edge notched and fatigue cracked 3 point bending specimen, $K_{id}$ is determined by equation (5):

$$K_{id} = \frac{P_{m} \cdot S}{BW^{1/2} \cdot Y(a/W)} \quad \text{.................................. (5)}$$

where, $P_{m}$ is maximum load after impact loading, $S$ is span of specimen supports and $Y(a/W)$ is configuration factor.

Fig.2. Specimen dimension of 3 points bending

To validate this $K_{id}$ from impact loading measurement, Crack Opening Displacement (COD) is also adopted to determine the corresponding $K_{id}^{COD}$. Crack Opening Displacement is taken from the nonlinear dynamic FE simulation and the expression for plane strain is:

$$COD(t)_{r,\theta=\pi} = K_{f}(t) \frac{8(1-\nu^2)}{E} \sqrt{\frac{r}{2\pi}}, \quad K_{f}(t) = \frac{V(t)E}{4(1-\nu^2)} \sqrt{\frac{2\pi}{r}} \quad \text{..............(6)}$$

Where $V(t) = COD(t)/2$ is the displacement of a nodal point of FE model located at a distance $r$ and $\theta = \pi$ from the crack tip.

Another calculation of $K_{f}(t)$ is from the strain readings and the expression is:

$$K_{f}(t) = \epsilon_{yy}(t)E\sqrt{2\pi r} = \frac{\sigma_{yy}(t)}{2\sqrt{2\pi r}}$$

$$\cos(2\sin(\sin(3\theta/2) - \theta)(1 - \sin(2\sin(3\theta/2))))$$

These three dynamic stress intensity factor calculations are mutually related on the state of applied load, material properties and damage parameters dealing with strain energy release rate and damage evolution for crack propagation.

4. Experimental procedure and FE modeling

4.1 The mechanical properties

Al6061 wrought product and AC8A cast aluminum alloy matrix were selected and alumina, SiC and carbon fiber were selected for reinforcement. Mechanical properties of these materials are represented at table 1.

Displacement controlled tensile tests were performed with a universal testing machine. Ram speed was 0.5 mm/min and 12.5mm gage length extensometer was used for measuring the strain. Specimen sized 6.5mm diameter and 65mm length were machined for smooth strain distance. The stress-strain curves for two aluminum matrix materials and for three different reinforcements are presented in Fig 3.
Table 1. Mechanical properties of Matrix and Reinforcements

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density (g/cm$^3$)</th>
<th>Tensile Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Thermal Expansion ($10^{-6}$/°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC8A</td>
<td>2.7</td>
<td>282</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>Al6061</td>
<td>2.7</td>
<td>290</td>
<td>72</td>
<td>25</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>3.15</td>
<td>2070</td>
<td>310.1</td>
<td>-</td>
</tr>
<tr>
<td>SiCw</td>
<td>3.2</td>
<td>5010</td>
<td>482.0</td>
<td>3.4</td>
</tr>
<tr>
<td>C$_{pan}$</td>
<td>1.5</td>
<td>2760</td>
<td>275.4</td>
<td>-</td>
</tr>
</tbody>
</table>

In this Study, the fabrication of MMCs was in liquid-state process that the MMCs of the matrix and reinforcements were fabricated by using squeeze infiltration method, after reinforcements had preformed by vacuum equipment. Casting ingots took the T6 heat treatment for improved mechanical and fracture toughness. Taking Rule of Mixture with the existed various tension test results, the basic mechanical properties as elasticity, yielding and stress flow were obtained and constitutive curves were fitted. For instance, the stress-strain curves of Al6061 based MMCs with the effect of hybrid and volume fraction are presented at Fig 5.

4.2 The dynamic toughness tests

As shown in Fig 2, specimen has fatigue crack to be 0.5~0.55W ($a=5.5$mm) with after 5mm depth of 0.2mm diamond wire cut for artificial cracking. Instrumented Charpy impact testing system (300J capacity) provides the impact force, displacement and time recording, while strain signal on the striker tup is recorded by through strain conditioning amplifier, and all the signals are synchronized.

All the specimens were tested at the range 5.17~5.25m/sec of the striker impact velocity, so that loading rate could be on the same level.

4.3 FE modeling

As the same of test specimen, FE model also has the sharp fatigue crack to avoid the notch and residual stress effect, so the free edge of elements along with an ascertain fatigue crack length was used for crack geometry. Mesh generation was built by using HyperMesh of Altair Engineering.

(a) 2D model with plane strain element  (b) Full 3D model with 3D solid element

Fig 4. Finite element mesh for 3 point bending specimen
To reduce the calculation time, plane strain 2D element was tried and full 3D geometric FE model was built to consider the constraint effect across thickness direction as shown in Fig 4 (a) and (b) for each.

For the mechanical properties of MMCs that is required at FE constitutive equations, several literatures’ methods were referred as for elastic, yielding and fracture stress flow, to identify continuous stress-strain flow [24]. The mechanical properties with respect to the change of volume ratio are shown at Fig 5, and stress-strain curves are presented also.

Fig 5. Mechanical Properties Changes & Stress-strain curve for damage parameters.

Fig 5 shows mechanical properties of Al6061 base MMCs also follow the “rule of mixture” ROM law in elasticity and ideal Yielding/Flow and fracture as shown well in Fig 5(a) and (b). By the reinforcements, the mechanical properties are improved as increase of yield and ultimate strength, but decrease of elongation.

To be characterized with this damage modeling is how to model the damage evolution to capture the onset of crack initiation. Elasto-Visco-Plasticity coupled with damage model motivate the direct evaluation of dynamic fracture toughness \( K_{Id} (t) \). To validate this damage model here, we present the comparison dynamic toughness being driven from equation (5), (6) and (7) between test and FE simulation. For damage model constitutive law, damage model law itself needs \( s_{SE}, \nu \) and conditions for damage threshold \( D_P \).

Finally, meso crack initiation conditions \( c_D \) is needed. From literature [22], \( s \) is assumed and fixed as 1, and others are identified from tension curves.

\( K_{Id} (t) \) perception of plane strain fracture toughness can be taken with two dimensional plain strain element that offers fine mesh to catch the meso crack propagation, which is a condition of RVE and its size can be assumed about 0.1mm of minimum element length in the continuum damage mechanics model.

Contact between hammer tup and specimen is defined with 2 dimensional master and slave interface and specimen surface to contact anvil is modeled with rotational joint element having contact length to corresponded specification of charpy impact standard.

To be verified this 2D plain strain element approach, all of conditions are same to the 3D full geometric model.

5. Results and discussion

In order to discuss the dynamic fracture toughness, \( K_{Id} \) from the computer aided instrumented Charpy impact testing is listed and \( K_c \) of previous our study [4] is also listed at table 2. Nonlinear Dynamic numerical FE analysis responding the dynamic nature of inertia at deformation, and damage parameters were applied in macroscopic \( K_{Id} \)
evaluation so that dynamic fracture process is explained in crack initiation and propagation. In this FE analysis, commercial FE simulation code of LS-DYNA developed by LSTC was used for AL6061 based matrix MMCs. 

\[ K_N \] and \[ K_{N, f} \] appeared in Table 2 depict the fracture toughness at the notch condition without fatigue precrack, so that notch sensitivity can be estimated.

Table 2. Fracture Toughness on various aluminum based composites

<table>
<thead>
<tr>
<th>Materials</th>
<th>Fracture Toughness ( (MPa \sqrt{m}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( K_N )</td>
</tr>
<tr>
<td>AC2B</td>
<td>26.2</td>
</tr>
<tr>
<td>Al/Al2O3-15%</td>
<td>16.7</td>
</tr>
<tr>
<td>Al/Al2O3-10%/C-5%</td>
<td>-</td>
</tr>
<tr>
<td>Al/Al2O3-20%</td>
<td>15.3</td>
</tr>
<tr>
<td>AC8A</td>
<td>-</td>
</tr>
<tr>
<td>Al/Al2O3-15%</td>
<td>-</td>
</tr>
<tr>
<td>Al/Al2O3-20%</td>
<td>-</td>
</tr>
<tr>
<td>Al6061</td>
<td>29.5</td>
</tr>
<tr>
<td>Al/Al2O3-15%</td>
<td>17.8</td>
</tr>
<tr>
<td>Al/Al2O3-15% (N)</td>
<td>-</td>
</tr>
<tr>
<td>Al/Al2O3-10%/SiC(_W)-5%</td>
<td>15.3</td>
</tr>
<tr>
<td>Al/Al2O3-10%/SiC(_W)-5% (N)</td>
<td>-</td>
</tr>
<tr>
<td>Al/Al2O3-20%</td>
<td>14.2</td>
</tr>
</tbody>
</table>

5.1 Dynamic Toughness behavior from experimental views

As shown in the table 2, three types of metal matrix composite used each different matrix alloy, AC2B, AC8A, Al6061 comprising with alumina and hybrid compositions were decreased in toughness, when it compared with that of matrix material only. In contrast with general understanding that mechanical properties of short fiber reinforced metal matrix composites are improved, but ductility of MMCs decreased remarkably. In the case of AC2B, ductility of alumina composite was decreased with the increase of volume fraction, as that elongation of Al/Al2O3-20% composite was decreased up to 9% compared with that of Al/Al2O3-15% composite in the tension test. Both static and dynamic toughness also reflect the same tendency. Presumably, the reduction of ductility in composites resulted in the deteriorating fracture toughness. In the case of AC8A based MMCs shows that the static fracture toughness of Al/Al2O3-15% and Al/Al2O3-20% composite was decreased up to 27% and 38% respectively compared with that of matrix only. In the case of Al6061 based MMCs, three effects of hybrid, volume fraction and notch on their fracture toughness shows the decrease of fracture toughness as the same of others matrix cases, and was decreased about 20% with the increase of volume fraction, about 14% lower than that of Al/Al2O3-20% when hybrid composition is compared with Al/Al2O3/SiC\(_W\).

In consequence, it can be known that static fracture toughness of MMCs was closely related with ductility of material, as well as volume fraction, type of reinforcements and matrix alloy. Dynamic fracture toughness under the dynamic loading condition presented same tendency to the static fracture toughness. In the case of AC2B based composites, \( K_{N, f} \) of Al/Al2O3-15% and Al/Al2O3/C was decreased about 40% when it was compared with that of matrix alloy. Hybrid composition was improved by 5% over that of Al/Al2O3-15%. These results are well reflected in elongation of carbon hybrid composites that is more effective in toughening than only alumina composites. Considering the notch fracture toughness, in the case of AC8A based MMCs, \( K_{N, f} \) of Al/Al2O3 composites was decreased with the increase of volume fraction due to a low ductility. In the case of Al6061 based MMCs, the hybrid effect of Al/Al2O3/SiC\(_W\)
composites resulted in the decreased of 10% than alumina only. When the static and dynamic fracture toughness were compared, dynamic fracture toughness is larger than that of static loading, that can be explained with strength increase related on the strain rate effect in general. From these results, the poor toughness of MMCs can be expected as a result of their high elastic modulus and low elongation to failure.

5.2 Damage modeling validation

It is noted that plane strain fracture toughness calls plain stain mode I fracture at the crack tip from the pre-cracked Charpy impact test, which is not accompanied by large-scale plastic flow. But the level of locality shows the larger plasticity and nonlinear force time history on to the failure. To investigate this local plasticity and its effect on fracture toughness, FE model with plain strain 2D element and 3D geometry were used in this study.

AL6061 based matrix composite is selected and impact force time history is compared as shown in Fig 6(b) in order that the local transverse stress flow changes can be examined. Comparison in deformation between 2D versus 3D shows very similar along with time as shown in Fig 6. 2D model shows slightly early and forward to crack initiation and propagation, but quite similar deformations are displayed up to final failure.

The force responses show the same maximum force and slop change when its value of 2D scaled with 8 times which can be presumed unit thickness model in 2D geometry with the plain strain, if the dominated force is under elastic and the other volumetric changes occur through thickness direction.

A sudden drop of force on the Al/Al₂O₃ and Al/Al₂O₃/SiCₘ composite appears where the force turns in to the crack initiation and propagation phase and it is remarkably short in its duration due to small elongation limit.

Fracture of composites is not the consequence of the growth of one dominant crack, but rather of process of nucleation, growth and coalescence of microscopic defects in a volume for new crack creation. As a consequence, a gradual decrease of deformation resistance is expected in composites and even macroscopic model should be better with progressive dynamic fracture, instead of sudden loss of strength in perfectly brittle fracture.

Moreover, the time of crack initiation is much more important to set dynamic fracture toughness and also toughness evolution should be evaluated at constant crack propagation with accumulating strain energy and release rate. Doubting 2D approach can not capture the constraint effect on the dynamic fracture toughness what if applied stress ahead of crack tip is seriously different in 2D modeling to the full 3D geometry model, the full 3D geometry model was taken by the terms of more realistic and reasonable results at applied stress.
distribution ahead of crack tip as followed Fig 7 and notes.

(a) Crack initiation and propagation at 2D plain strain element

(b) Crack initiation and Propagation at 3D element

(c) Plastic zone development near the crack tip

Note 1. Crack initiation starts about $T=1.5\text{msec}$, and continued crack propagation is depicted at $T=1.7\text{msec}$.

Note 2. Plastic zone over yield stress implies a series of damage processes evolving stretch zone development, void nucleation and growth, onset of crack growth, void coalescence, first crack advance, continued dimple rupture (or cleavage), those of plasticity processes are fully coupled with damage model controlled by equation (4)

Note 3. Enveloped plastic zone differs with thickness direction, mirrored elliptical shape on the surface and cylindrical shape at the central distance.

Fig 7. Applied stress distribution ahead of crack tip
5.3 Dynamic Fracture Toughness from FE damage model

From the 3D damage model, the crack opening displacement (COD) is measured directly from the point located at a distance \( r \) and \( \theta \), and then evolution of dynamic stress intensity factor to the crack propagation is calculated by using equation (6).

Fig. 8(a) shows crack opening displacement \( COD(t), r=0.5 \text{mm}, \theta=\pi/2 \) for a crack length of 5.5mm, at \( r=0.5\text{mm} \). Each displacement shows well the presumable onset of crack initiation by the sudden slope change. Before crack initiation, crack tip blunting is apparently shown with the same deformation rate and it is noted that damage evolution at about the crack tip can be developed with deformation or after crack tip blunting. Al/Al\(_2\)O\(_3\)-15% is earliest to turn into the commencement of crack propagation. Al/Al\(_2\)O\(_3\)/Si\(_{CW}\) shows intermediate crack propagation start and Al6061 is latest for crack propagation and crack arrested during crack propagation with change of displacement rate.

It is should be noted that damage model can be used for determination of fracture time directly with transition of displacement rate, and moreover the evolution of dynamic stress intensity factor can be fully plotted to pinpoint the criteria of dynamic fracture toughness \( K_{id} \).

To ensure FE damage model for evaluation of dynamic fracture toughness \( K_{id} \), the evolution of \( K_{id} \) is plotted as show Fig 8(b) and then compared with dynamic fracture toughness from the instrumented Charpy impact test. The comparison between test and FE simulation was summarized at table 3.

Table 3. Comparison of experiment and simulation results in dynamic fracture toughness

<table>
<thead>
<tr>
<th>Materials</th>
<th>Fracture Toughness (MPa(\sqrt{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
</tr>
<tr>
<td>Al6061</td>
<td>35.4</td>
</tr>
<tr>
<td>Al/Al(_2)O(_3)-15%</td>
<td>26.5</td>
</tr>
<tr>
<td>Al/Al(_2)O(<em>3)/Si(</em>{CW})-5%</td>
<td>23.7</td>
</tr>
</tbody>
</table>

FE damage model shows acceptable coincidence with 6.2 to 13.4 % errors against the test values as well as very similar tendency as volume fraction and hybrid effect decreasing the dynamic toughness. Dynamic toughness calculation using equation (7) of stress measurement is supplemented as shown in Fig 14(a). Stress of solid element located at the same distance from crack tip as COD measurement is plotted and vertical stress component with respect to artificial crack direction is used. This vertical stress component (remarked SigmaXX) is the maximum principle stress that can be regarded as major contribution for crack propagation. This stress component is very high over yield stress of uniaxial tension test in general whereas effective stress is still tolerable to sustain damage evolution coupled with elasto-plastic stress flows under material constitutive law of equation (4) and uniaxial stress-strain curve fitting of power law. It is should be mentioned that stress history ended.
when the solid element reached in to critical damage of meso crack initiation allowing crack propagation.

(a) Stress history with \( \text{Stress}(t)_{\text{same, } \beta} = 5.0 \) mm

(b) \( K_{\text{id}} \) evolution from stress measurement

Fig 9. Stress time history & \( K_{\text{id}} \) evolution from FE damage model

Based on this applied stress history ahead of crack tip, dynamic stress intensity factor can be plotted as shown in Fig 9(b), designating \( K_{\text{id}} \) evolution of dynamic fracture toughness by onset of element failure. Beside the numbers of dynamic fracture toughness of COD base, Stress base dynamic toughness that is derived from applied stress ahead of crack tip is appeared in table 3 with a round bracket. Slight high numbers is deemed that applied stress measured at surface of specimen as the same way on the general test methods by using attached strain gage on the specimen surface is higher. But the small value in case of Al/Al\(_2\)O\(_3\)/SiC\(_W\) is not clear and need to be considered numerical stability at FE calculation under the shock wave transmittance at relatively small deformation.

In addition, whole structural potential energy absorbing capacity of composites is reviewed as shown in Fig 10. As the results of fracture toughness is generally lower than that of monolithic aluminum alloy, composites show energy absorption is slightly higher than that of monolithic Al6061, whereas strength and stiffness is remarkably improved as the mechanical properties. It is due to less deformation limit across the specimen of composites.

6. Conclusion

In this study, the static and dynamic fracture toughness tests of commercial aluminum based composites were implemented and continuum damage model was applied on dynamic toughness test. The main deliverable of this study are:

- Fracture toughness of MMCs is decreased as the volume fraction of alumina increase. Main reason of toughness decrease can be attributed to the loss of ductility in composites.

- Dynamic fracture toughness is slightly increased when it is compared with that of static fracture toughness, due to loading rate hardening.

- FE simulation with elasto-visco-plasticity fully coupled with damage model shows remarkably good correlation with experimental dynamic fracture toughness. Especially, direct measuring COD ahead of crack tip at real time is good agreement with test, showing 6.2 to 13.4 % errors. In measuring stress, simulation gave the errors from 4.2 to 18.5%.

- 2D plain strain element approach is not acceptable to simulate this small specimen
of dynamic toughness test. 3D full geometry FE model is feasible for considering the constraint effect across specimen thickness and crack propagation.

- FE damage modeling is useful to estimate the dynamic fracture toughness directly with damage criteria for meso crack initiation.
- To understand and explain dynamic fracture process, FE damage modeling and parameters based on mesoscopic view is useful method to link up with many macroscopic parameters in analysis of stress, strain, and stress intensity factor and to give the 3 dimensional illustration of various parameters.
- Continuum damage model is ideally suited for dynamic fracture toughness determination of aluminum matrix composites. Instrumented Charpy impact test result for dynamic fracture toughness of aluminum matrix composites is assured with FE simulation coupled with continuum damage mechanics model.

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