

Microcracks propagation in one Al/SiC_p under impact loading*

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Abstract. Numerous microcracks propagation in one metal matrix composite, Al/SiC_p under impact loading was investigated. The test data was got with a specially designed impact experimental approach. The analysis to the density, nucleating locations and distributions of the microcracks as well as microstructure effects of the original composite was received particular emphasis. The types of microcracks or debonding nucleated in the tested composite were dependent on the stress level and its duration. Distributions of the microcracks were depended on that of microstructures of the tested composite while total number of microcracks in unit area and unit duration, was controlled by the stress levels. Also, why the velocity was much lower than theoretical estimations for elastic solids and why the microcracks propagating velocities increased with the stress levels' increasing in current experiments were analysed and explained.

1. INTRODUCTION

Spallation in solids is caused by short-lived tensile pulse resulted from the intersection of reflected compressive waves. Previous studies showed that the spallation results from nucleation, growth and coalescence of microcracks in solids [1, 2]. The microcracks occur in solids in short durations of 1 μ s so their propagation is controlled by amplitudes and durations as well as shapes of stress pulses. As indicated in previous researches, to study numerous microcracks propagating, problems such as how to trace and observe the microcracks at a very short duration must be considered. So far evaluating evolutions of such microcracks requires the proper loading device and the adequate measurement technique for the microcracks characteristics [3-5]. Usually, in planner impact tests, stress durations can simply be made as short as the time required for the nucleation, growth and coalescence of the microcracks and then damages can be caught up, or “frozen in”, at each stage of the damage development. For instances, a wedge geometry impactor was designed [3] for the study of the effect of stress duration on spallation in metals. By this technique, the point of initial spallation can be determined and the impactor thickness at the point corresponds to the minimum flyer thickness for a certain impact velocity to initiate a crack. Hence it revealed qualitatively a characteristic period of nucleation for spall-cracks. However in this case, stress duration is continuously changed along the wedge direction and it is difficult to get quantitative data of the microdamage evolution through experiments with this kind of tapped impactor. Another plate impact method was applied for producing a controlled pattern of internal penny-shaped cracks with a pre-determinable size distribution in poly-carbonate [4]. The method entails backing the flyer plate with a plate containing holes of various sizes, using a gas gun to accelerate the flyer assembly and impacting this assembly against a specimen plate. These experiments gave enlightenment that there is some possibility for producing damage of different stress levels or at different stages in the same specimen in one shot.

Based on the method [4] and inspired by the short stress pulse technique, with which stress durations can attain to the order of 100 ns [5], one specially designed plane impact approach [6] was adopted to obtain samples with progressively damage levels under one load level but with different duration.

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With this method, resultant test data on microcracks' developing in one metal matrix composite, containing SiC particles, were obtained. Based on analysis to microstructure effect, the microcracks' propagating in the tested material has been presented [7]. The results indicated that, at initial evolution, microdamage always appeared as particles' cracking and debonding at interfaces between particles and matrix. The distributions of the microdamage were similar to that of the particles in the tested composite. With stress duration increased, these microcracks developed and form macrocracks in the samples. Consequently, the resultant microcracks' propagating velocity was dependent on the load levels, the higher the stress level, the faster the microcracks propagate. However it was hard to follow and understand such conclusions on microcracks' propagating. Motivated by previous researches and the need to better understanding how fast these microcracks propagate, in current study, detailed analysis is applied to the previous test data again and it focus relationships between microcracks' distributions and microstructure effects of the tested material as well as microcracks nucleation, propagation.

2. EXPERIMENTS PROCEDURES

2.1 Materials and experiments [7]

The material used in this experiment was extruding rods of an Al/SiC_p, in which the size of SiC particles is about 20 μ m and their volume fraction is about 10%. Fig 1 presents close-up observation to the original composite. As showed in this figure, besides the SiC particles, large particles with dark colour in the photo, small second phase particles could be seen in matrix of the composite. Table 1 presents the main components and principal mechanical property of the composite. In addition, the density of total particles, including SiC particles and second phase particles in the Al-alloy, n_A , equivalent diameters, d_p , volume fraction, f_{vp} (%), as well as mean free distance between two nearest neighbouring particles, g λ_p , are also showed in this table. The details on the data in Table 1 have been reported in previous study [7].

A light gas gun was adopted to carry out the microdamage evolution tests. In order to follow the evolution of microcracks occurring under impulse loading, a specially designed experimental approach was applied to obtain the progressively damaged samples under the same load-amplitude but the loading

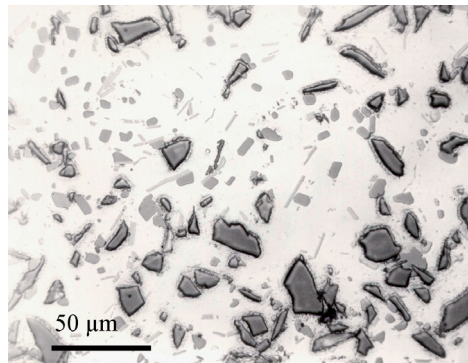


Figure 1. Micrograph of the original Z1101Al/SiC_p.

Table 1. The principal property and microstructure parameters of the original Al/SiC_p.

Material	Main Components		Density (g/cm ³)	σ_b (MPa)	E (GPa)	n_A (/mm ²)	d_p (μ m)	f_{vp} (%)	λ_p (μ m)
	matrix-Al	SiC particle							
Al/SiC _p	$\sigma_b=205$ (MPa)	$d_{SiC}=20\mu$ m $f_v=10$ %	2.74	365	80	2447	12.2	19	10.3

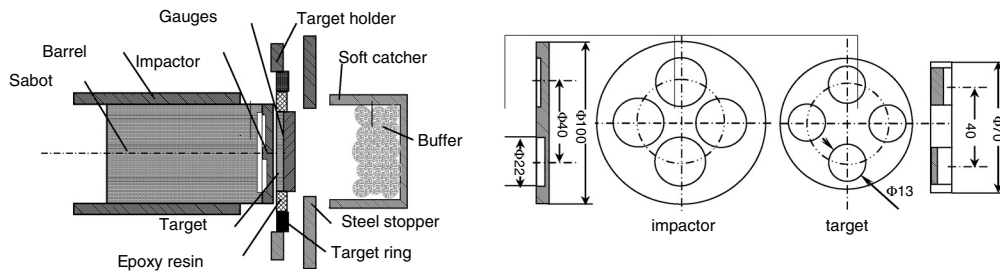


Figure 2. a. The scheme of the planar impact apparatus. b. A set of special designed flyers and targets.

durations. Fig.2a and 2b are the scheme of the planar impact apparatus and a set of flyers and targets. As showed in the figure, in the impactor, four small flyers with diameters of 22 mm and different thickness could yield different pulse durations during impact. In the target, four small target plates, with diameter of 13 mm, were put respectively at locations corresponded to where four small flyers placed. Be sure the one-dimensional strain loading condition, the thickness of target plates was calculated according to stress pulse duration and the target diameter. Additionally, the rotation of the projectile launched in the gun tube was less than $1-2^\circ$, which guarantees the success of simultaneous measurements of four profiles in one shot [6]. After soft recovery, each small target was sectioned along its diameter and then finely polished to mirror-like and scratch-free for close-up observations. Optical microscope and SEM were adopted to check the damage zones in each sample and Image Analysis was used to measure the length, number and distribution of microcracks in the sample.

2.2 Experimental Results

Five sets of spalling evolution tests were carried out. The impact velocity was preset as $250\text{ m/s} \sim 480\text{ m/s}$, the amplitude of tensile stress was around $2.1 \sim 3.5\text{ GPa}$ and stress duration $0.08 \sim 0.44\ \mu\text{s}$. Microscopic observations showed that microdamages always occurred in samples under short stress durations of $0.08 \sim 0.22\ \mu\text{s}$. In particular under higher stress level, the most microdamage was particle-cracking and a few interface-debonding could be seen. Fig.3a presents a damaged region in the sample under stress level of 3.5 GPa and duration of $0.08\ \mu\text{s}$, in which, the microdamage in the sample was almost particles' cracking. But in the sample under lower stress level and longer duration, microdamage appeared was particles' debonding along the interface of particles and matrix. Fig.3-2 shows such microdamage in the sample under the stress level of 2.7 GPa and the duration of $0.15\ \mu\text{s}$.

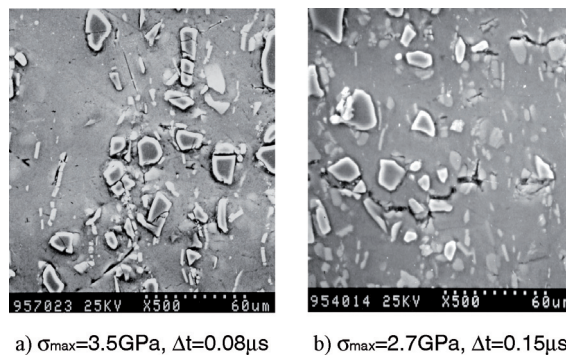


Figure 3. Micrographs of microdamage in the progressively damaged samples.

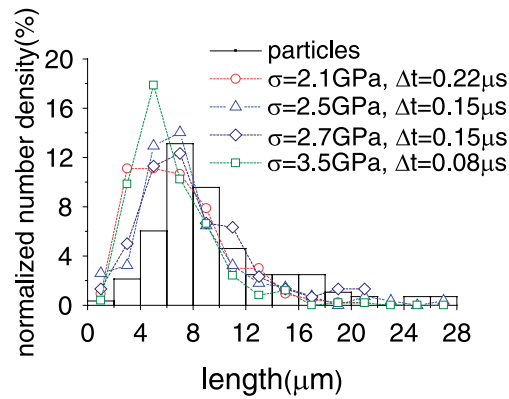


Figure 4. Normalised number density of micro-cracks occurred in microdamaged samples (symbol) and that of total particles in the composite (column).

The quantitatively further microscopic observations of these microdamage are showed in Fig 4, in which symbols denote distributions of normalised number density of microcracks occurred in the microdamaged samples. As a comparison, the normalised number density of total particles (SiC particles and second phase particles in the matrix phase) in the original composite was drawn by columns (Fig.4). The experimental data showed that, in current test ranges, i.e. $\sigma = 2.1 \sim 3.5$ GPa, $\Delta t = 0.08 \sim 0.22 \mu s$, the distributions of microcracks in the damaged samples were not out of that of particles in the original composite, which agreed with the results of microscopic observations in Fig.3. As mentioned above, in the sample under $\sigma = 3.5$ GPa, $\Delta t = 0.08 \mu s$, the micro-cracks with the length of 3~5 micron was about 20% in unite area; while at lower stress level and longer stress duration, the peaks of number density of micro-cracks were around 15%, lower than the former. Obviously, the distributions of number density of microcracks are dependent on that of particles in the original composite and types of microdamage, microcracks or debonding, are sensitive to stress levels and durations.

Table 2 presents experimental data on the microcracks in the damaged samples, in which, n_c is the density of microcracks, total count of the microcracks in unit area of damaged regions; d_c equivalent length of the micro-cracks. In addition, considering the fact that the density of micro-cracks in each damaged sample is likely equal to that of particles in the original composite, let the volume fraction of microcracks, f_{vc} , equal to that of particles, f_{vp} , namely $f_{vc} = f_{vp} = 19\%$ (Table 1). So the free distance between two nearest neighbouring microcracks in each damaged sample, λ_{ci} , could be obtained as shown in Table 2. The details about how to get the data in Table 2 was depicted in the reference [7].

Table 2. The experimental data on the micro-cracks in the damaged samples.

Stress level σ_{max} (MPa)	$\sigma_{max}\Delta t$ (MPa· μs)		Density of microcracks n_c (/mm ²)	Equivalent length of microcracks, d_c (μm)	Mean free distance of microcracks, λ_c (μm)	note
	nucleation	propagation				
3.5×10^3	280	105	2637	11.3	9.9	here, the volume fraction of micro-cracks, $f_{vc} = f_{vp} = 19\%$
2.7×10^3	405	189	2383	12.3	10.4	
2.5×10^3	375	175	2208	12.8	10.8	
2.1×10^3	462	234	2288	12.6	10.6	

The experimental samples could be divided into two parts in accord with the damage grades. In one part of samples, a lot of microcracks with the length of microns could be seen (Fig.3). Fig.5 gives the σ -t plane. In the figure the stress level and stress duration of these damaged samples are plotted by symbol "△". These symbols "○" showed that, both the stress level and its duration determined if the microcracks nucleated or not in the tested composite.

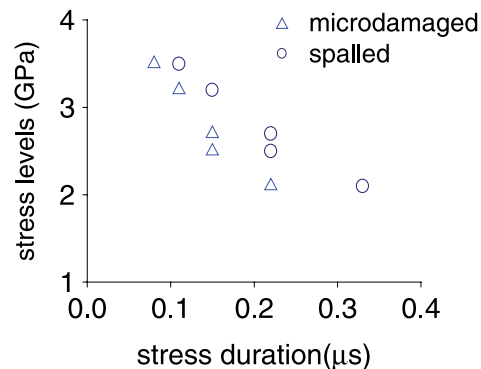


Figure 5. Plots of maximum tensile stress levels and their durations for the progressively damaged samples.

In another part of samples, macrocracks with lengths of the order of millimetre appeared so these samples were called as spalling samples. Also, in Fig.5, the symbol “o” indicates the spalling samples and one spalling curve can be drawn, above which the samples spalled. Clearly, both stress level and stress duration controlled the spallation in the tested composite and under higher stress level, the spalling would occur in shorter stress duration; while under lower stress level, spalling would take longer duration.

In fact, Fig.5 not only presents the evolution between microdamaged samples and spalling samples, but also shows visibly propagations of the nucleated microcracks, which would be discussed later.

3. ANALYSIS AND DISCUSSIONS

3.1 On microdamages

The experimental observations showed in Fig.3 revealed, a) the microdamage, occurred in the samples under higher stress level and relative short stress duration, was almost particle-cracking; and b) the microdamage was always debonding at interface between particle and matrix under relative lower stress level and longer durations. One simply analysis could be given as followings.

The acoustic velocity of aluminium alloys is about 5000m/sec.and the mean diameter of SiC particles in the composite was about 20 microns. During the stress duration, saying about 0.1μs, the tensile stress wave would go up and down in one particle about 25 times. If the stress duration is about 0.2μs, the stress wave would go up and down in one particle about 50 times. In addition, thickness of the interface between the particle and matrix is much smaller than the mean length of SiC particles. So, the loading on both the particles and the interface in the composite can be regarded as quasi-static. In current tests, the strength and elastic modulus of SiC particles in the composite were much higher than that of the matrix. As a result of stress wave, the microcracking would occur readily in the particles under higher tensile stress levels and shorter durations. Once particles cracking, the stress relaxed and it was not easy for the interface between the particle and the matrix, to be debonding. Obviously this was estimated based on that SiC particles were sphere-like with given diameter and the stress durations was very short. While the amplitude of lower stress levels was not higher enough to make the particle cracked, in this case, even if its duration was longer, debondings may occur at the interface, as shown in Fig.3-2. The similar phenomena were also reported in previous study on one Al-alloy [2]. Actually, the stress duration was another factor which can affect microdamage types. In Dixon’s research [8], there was no evidence of cracking in SiC particle in the spallation samples, on which the stress level varied in 1.2~4.0 GPa and the stress duration was 0.3 μs, longer than that in current study. Additionally, in static tensile tests on aluminium containing hard SiC particles, the initial

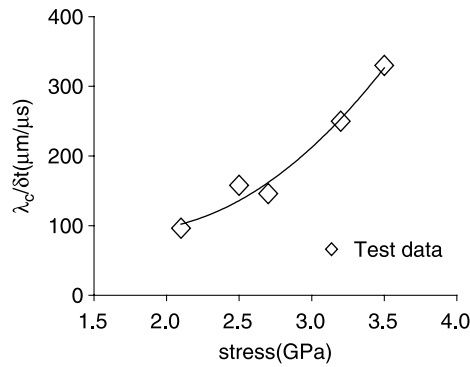


Figure 6. Plots of the microcracks propagation velocity, $\lambda_{ci}/\delta t_i$, against stress levels, σ_i , in current tests range.

microdamage always was debonding at the interface between particles and the matrix [9]. Consequently, the types of microdamage, microcracks or debonding, occurred in the tested composite is indeed related to the stress level and its duration.

3.2 Microcracks development

As showed in Figure 3 and 4, the distributions of microcracks and debonding occurred in short durations were similar to that of microstructures in the original composite. And the total number of microcracks in unit area was controlled by stress levels (see Table 2). The results indicated that, these microcracks occurred at the short duration was at the initial development of these microdamage. Since the initial development of microcracks under short stress pulses have been analysed in previous study [2], in this paper, such aspect was not discussed in detail and the focus is on microcrack propagations.

It is manifest that Fig.5 presents two important stages during evolution of microdamage related to spallation. One was the initial development of microcracks shown in Fig.3 and another the propagation and coalescence of these microcracks. It revealed that, at the same stress level, only after a short interval, microcracks nucleated in samples developed to form macrocracks in the order of millimetre and spalling occurred. Obviously, the interval was the difference between two durations, nucleation and spallation. Noticing nucleated microcracks always occurred in the particles (Fig.3) and the distributions were similar to that of particles in the tested composite (Fig.4), the distance these microcracks traversed over, during the interval, should be the free distance between two nearest neighbouring microcracks. Thus, under the same stress level, σ_i , the microcracks propagation velocity, v_i , could be given as:

$$v_i = \frac{\lambda_{ci}}{\delta t_i} \quad (1)$$

where λ_{ci} is the free distance between two nearest neighbouring microcracks and δt_i is the interval. Fig.6 presents plots of the propagation velocity, v_i , against stress levels, σ_i . As shown in this figure, the microcracks' propagation velocity increases with the stress level under given test conditions and the maximum velocity is about 340 m/s corresponding to the stress level of 3.5 GPa and the stress duration of 0.08 μs ; the minimum velocity is about 100 m/s under the stress level of 2.1 GPa and the duration of 0.22 μs .

About the microcracks propagating velocity showed in Fig.6, there are two unclear: a) the velocity was much lower than theoretical estimations and experiment results for elastic solids; and b) for the same tested composite, why the microcracks propagating velocities increased with the stress levels' increasing.

Ordinarily, for one macrocrack in elastic solids, its growth speed is about 0.4 time of velocity of Rayleigh-wave. According to the theoretical estimating, the macrocrack growth speed is about 2000 m/s for Al-alloys. However, previous study on macrocrack propagations in metals [10] indicated that, in environments of plastic regions and temperature changes, macrocrack growth speed was not the theoretic value but dropped down quickly. Considered current loading conditions, before the tensile stress wave, the samples experienced impact compress wave with amplitudes of 2.1~3.5 GPa firstly. Under such high compress loadings, the matrix phase, Al-alloy, of the tested composite should be plastic deformed, so in the matrix phase microcracks propagating velocity would drop down. This analysis can apply to the cases under higher stress level of 3.5 GPa. As shown in Fig.3, under $\sigma_i = 3.5$ GPa, microcracks always nucleated in particles of the composite while its duration is 0.08 μ s; under the same tensile stress pulse, after a short interval, saying 0.03 μ s, the microcracks nucleated in particles would grow up from the particle to the matrix phase through the interface between the particle and matrix phase.

Whereas the matrix phase was going strong plastic deformation. Thus in this case, the velocity of the microcracks which traverse the deformed matrix between two nearest neighbouring microcracks was of course much slower than that got in the solids without plastic deformation. Thus in this case, the velocity of the microcracks which traverse the deformed matrix between two nearest neighbouring microcracks was of course much slower than that got in the solids without plastic deformation. Therefore, the velocity of 340 m/s is reasonable and its magnitude can be comparable with previous study on velocity of cracks in plastic zones for metals [10]. As a result of short interval, this estimation does not take into account with microcracks' branching and linking as well as interactions. As for why the microcracks propagating velocities increased with the stress levels' increasing and duration decreasing, it may consider characteristic of microcracks in current experimental results. Current experimental observations presented that initial microcracks were particles' cracking and debonding under higher and lower stress levels, respectively. And the velocity of microcracks from the particles to the matrix phase was faster than that from interface to the matrix phase. Furthermore, the faster velocity was corresponding to the higher stress levels and shorter durations, whereas the slower one corresponding to the lower stress levels and longer durations. It could be seen that microcracks propagating is very sensitive to the sharpness of initial cracks, whose variation determines the relative breaking stress. As indicated in the previous studies on macrocrack's propagations [10], the velocity of one macrocrack with a tip of larger radius was faster than that with a tip of smaller radius, or the velocity of one crack with a sharp tip was slower. The previous study could help us to understand what appeared in current impact experiments.

Consider the samples with particles' cracking first. As shown in Fig.3a, under the stress level of 3.5 GPa, microcracks in particles would propagate from particles to the matrix phase, as analysed above, from one brittle material to another high plastic region. While initial growth, microcracks' tip would become obtuse due to the interface between the particle and matrix. Thus the higher breaking stress made the faster propagation. For the debonding, it could be regarded as a microcrack at the interface and would propagate along the interface under lower stress levels. Once these cracks propagated transverse from the interface to the matrix phase, their tips were not as obtuse as those particle-cracks'. So their velocity was slower than the particles' cracks. Meanwhile, the slower the propagating velocity and the lower the stress levels were concomitant. In additions, due to longer durations, some factors, such as microcracks' branching and linking as well as interactions, had to be taken into account in the microcracks propagation. That is why the velocity of microcracks under lower stress levels and longer durations are always slower than that obtained under higher stress levels and short durations.

4. CONCLUSIONS

The present study investigated numerous microcracks' propagations occurred in one typical Al-alloy reinforced with SiC particles under impact loadings. The analysis of the density, nucleating locations and distributions of the microcracks and microstructure effects of the original composite was received

particular emphasis to explain the current experimental results. The following conclusions have been deduced.

- (1) An experimental technique was adopted to follow successfully the evolution of microcracks occurring in one Al/SiC_p under impulse loading;
- (2) The initial microcracks were particles' cracking and debonding at interface between particles and matrix. The types of the initial microdamage were related to the stress level and its duration. Their distributions depended on that of microstructures of the original composite;
- (3) The propagating velocity of the microcracks was much slower than theoretical estimations for elastic solids. It was clearly because of that, in current study, the matrix phase was going strong plastic deformations before the tensile pulse loading. The velocity of microcracks propagated in the plastic regions was much lower than that in the elastic solids;
- (4) Why the microcracks propagating velocities increased with the stress levels' increasing and duration decreasing was explained by the characteristic of microcracks nucleated in the particles and the interface between particles and matrix, which was related to the stress levels and durations. In addition, with stress duration longer, microcracks' branching and linking as well as interactions would make their propagation velocity slower.

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