Yamagata *et al. Appl Adhes Sci (2017) 5:7*
DOI 10.1186/s40563-017-0087-7

Applied Adhesion Science

RESEARCH Open Access

Experimental investigation of mode I fracture energy of adhesively bonded joints under impact loading conditions

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Abstract

Double cantilever beam (DCB) tests under impact loading conditions were conducted using a falling-wedge impact test machine and a high-speed camera. The change in mode I fracture energy G_{IC} was investigated in comparison with the results obtained under the quasi-static loading condition. Two types of adhesives with significantly different mechanical properties were used for the DCB tests, and the change in rate dependency of the adhesive types was observed. Adhesively bonded joints have been widely used in various engineering products, such as automobiles, ships and airplanes. The strength of the joints is important for product safety. To evaluate the mode I fracture energy of adhesively bonded joints, DCB tests have been standardized under the quasi-static loading condition. Additionally, several tests have been proposed to evaluate the impact resistance of the joints. However, impact loading makes it difficult to evaluate the fracture energy accurately because of the dynamic effects. Therefore, specialized evaluation methods for dynamic fracture must be considered, and a load-independent analysis of the fracture energy was used to avoid load measurement problems due to the dynamic effects in this study.

Keywords: Adhesive bonding, Double cantilever beam test, Impact test, Mode I fracture energy, Rate dependency

Background

Recently, the automotive industry has paid attention to multi-material structures to reduce CO_2 emission. Hence, the use of light-weight and high-strength materials such as Al–Mg alloys, high-tensile-strength steel and carbon-fiber-reinforced plastics (CFRP) is essential to lighten the vehicle weight [1]. Joining methods for these dissimilar materials are the key to apply them into the structural part of the vehicles in combination. When the CFRP is jointed with other materials, welding, which is one of the most standard joining methods for vehicles, cannot be applied, and other methods must be considered. When dissimilar materials are jointed, thermal deformation at the joints often becomes a problem because of the difference in thermal coefficient of expansion, and reduction methods must be considered. Adhesive bonding can be applied to the joint among various types of materials to overcome these issues, as well as absorb vibration, prevent electrolytic corrosion, seal clearances, etc. Therefore, adhesive bonding can be one of the leading joining methods for the structural part of vehicles.

The fracture energy of adhesive joints can be experimentally measured using the double cantilever beam (DCB) test method for mode I fracture [2]. However, this test is only standardized under the quasi-static condition. Conversely, the strength of the joint at high loading rates is an important issue for the safety of vehicles. Block impact tests [3] were conducted for the fracture strength in shear, whereas impact wedge-peel tests [4] and DCB tests with a hydraulic tensile test machine [5] were conducted for the mode I fracture energy in a wide range of loading speed. These methods have difficulty in measuring the load because the dynamic effects are significant. Additionally, an asymmetric fracture is observed when one side of the DCB specimen is pulled at a high speed [5]. To measure the mode I fracture energy under the impact loading condition in another manner, a falling-wedge impact test machine using a DCB specimen was proposed by Xu et al. [6]. An opening displacement and a crack length are measured with a high-speed camera. With a load-independent analysis, the fracture energy can be calculated without measuring the load. Therefore, the difficulty of the G_{IC} measurement because of the dynamic effects can be avoided. Additionally, the specimen symmetrically fractures because of the symmetrical wedge shape. The change in G_{IC} with the testing temperature has been investigated using three different epoxy adhesives in Ref. [6].

In this study, two types of adhesives are used to fabricate the DCB test specimens: a two-component type epoxy adhesive and a single-component type polyurethane adhesive. From the viscoelastic viewpoint, the glass transition temperature T_g can be a key factor for the rate dependency of G_{IC} of the adhesively bonded joints [6, 7]. Because T_g of standard epoxy adhesives is much higher than the room temperature, the standard epoxy adhesives tend to be brittle. Hence, lower rate dependence is expected in the impact tests at room temperature. Although the polyurethane adhesives designed for structural usage can absorb much more energy in fracture than the epoxy adhesives [8], high rate dependence is expected because of the lower T_g and ductile behavior. The effect of the loading rate on the G_{IC} values for brittle and ductile adhesives is experimentally investigated with the falling-wedge impact testing machine.

Experimental

Double cantilever beam test specimens

The dimensions of a substrate are: length $l = 188$ mm, width $b = 24.8$ mm, and thickness $h = 2.0$ mm, as shown in Fig. 1. Polytetrafluoroethylene (PTFE) sheets (thickness: 0.1 mm) were inserted between the substrates to control the adhesive layer thickness. Although the pre-crack length of the specimen was set to 50 mm to insert the PTFE sheet, an initial crack front is not sufficiently sharp, and overestimation of the G_{IC} value is expected at the first part of the crack propagation. Therefore, the initial stage of the fracture was omitted, and the data with the crack length over 60 mm were used to calculate the G_{IC} value.

Spring steel (SUP-10) was selected as the substrate material to prevent plastic deformation of the substrate during the test. The surfaces of the bonded area of the spring steel was sandblasted with Al_2O_3 grit and wiped with acetone before bonding. The epoxy adhesive (DENATITE 2204, Nagase Chemtex Corp., Osaka, Japan, curing condition: 100 °C for 30 min) and polyurethane adhesive (Penguin Seal, Sunstar Engineering Inc., Osaka, Japan, curing condition: 24 °C for a week) were used. For the polyurethane

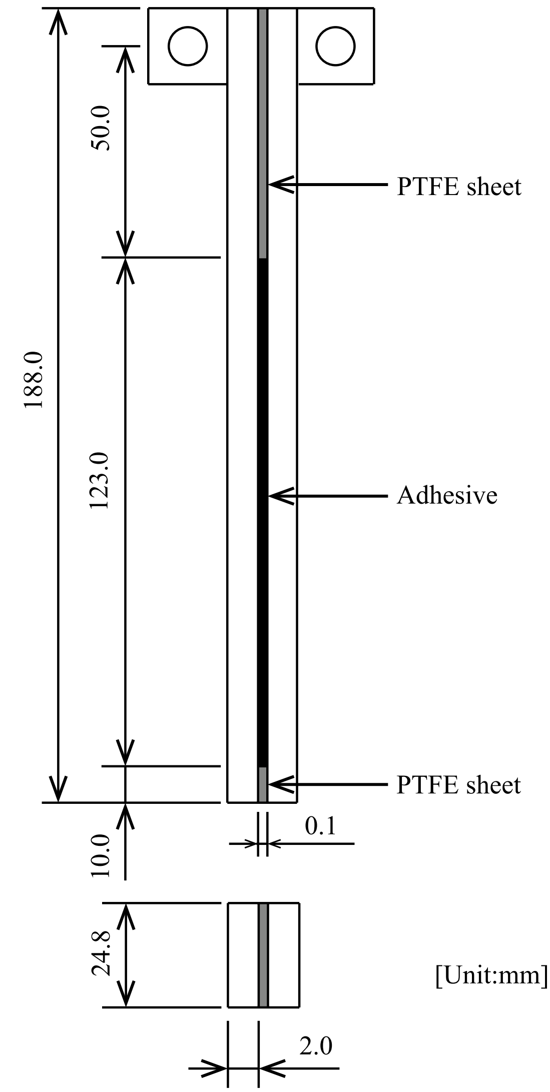

Fig. 1 Double cantilever beam (DCB) test specimen

adhesive, a prototype primer (Sunstar Engineering Inc., Osaka, Japan) was applied to the bonding surface in advance. The mechanical properties were measured with the tensile test using the dumbbell-shape adhesive specimens, as shown in Table 1.

Double cantilever beam test

Quasi-static DCB tests were conducted three times for each adhesive with a tensile test machine (STB-1225S, A&D Co., Ltd., Tokyo, Japan), as shown in Fig. 2. The crosshead

Table 1 Mechanical properties of the epoxy and polyurethane adhesive

Adhesive	Young's modulus	Maximum stress	Failure strain (%)
DENATITE2204	5.34 GPa	47.7 MPa	1.15
Penguin seal	4.62 MPa	Approximately 6 MPa	Approximately 1000

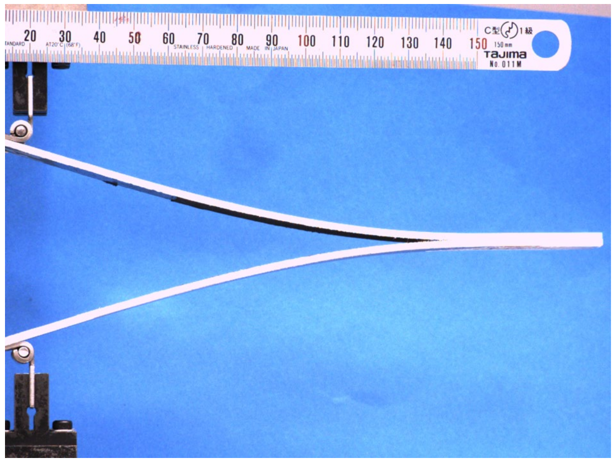

Fig. 2 CCD camera photograph to measure the crack length and displacement during the quasi-static DCB test

speed was 5 mm/min. The test temperature was 24 °C. The loading value was measured with a load-cell attached to the tensile test machine. The opening displacement and crack length were measured with a CCD camera (DFK 23U274, The Imaging Source Europe GmbH, Bremen, Germany).

The impact DCB tests were conducted three times for each adhesive with a falling-wedge impact test machine, as shown in Fig. 3. During the test, the wedges descended and passed through the pins, which were inserted in aluminum blocks and fixed to the end of a DCB specimen, as shown in Fig. 4. The fracture process during the test was recorded with a high-speed camera (CRYSTA, PI-1PS, Photron Co., Ltd., Tokyo, Japan). The height of the drop weight was set to 0.72 m, and the mass including the wedge was 13.4 kg. The test temperature was 24 °C. From the obtained pictures, the crack length and the opening displacement were measured manually, whereas resolution of the pictures was 0.2 mm per pixel.

Results and discussion

Calculation of the fracture energy

Mode I fracture energy G_{IC} based on the linear elastic fracture mechanics (LEFM) is determined by

$$G_{\mathrm{IC}} = \frac{P^2}{2b}\frac{dC}{da}, \tag{1}$$

where a is the crack length, b is the width of the specimen, P is the applied loading, C is the compliance ($C = \delta/P$), and δ is the opening displacement. The compliance can be expressed using Euler beam theory as

$$C = \frac{\delta}{P} = \frac{2a^3}{3EI}, \tag{2}$$

where E and I are the Young's modulus and second moment of area of the substrate, respectively. Using the corrected beam theory (CBT), the fracture energy can be expressed as a function of the load, displacement, and crack length [9]:

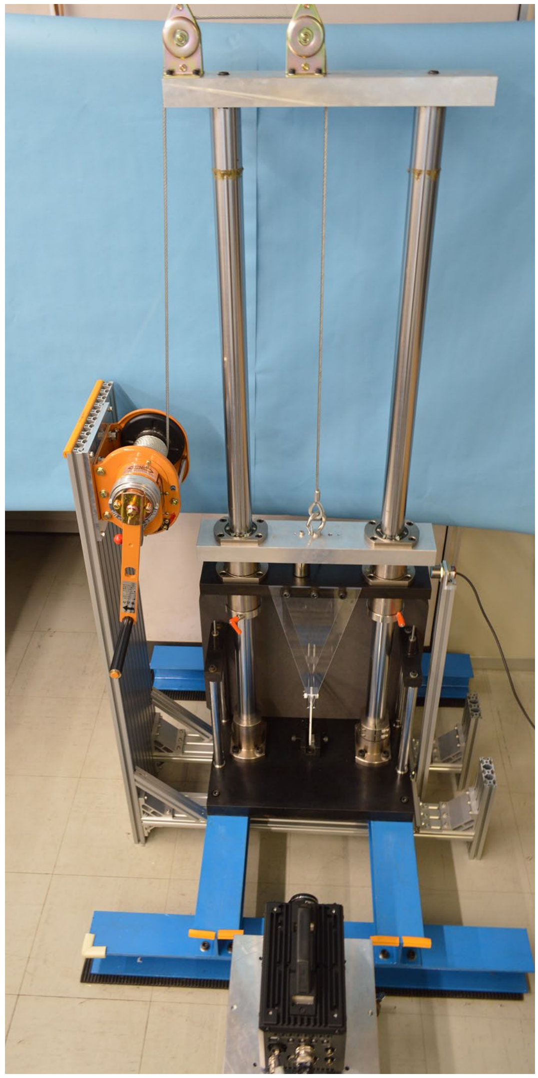

Fig. 3 Experimental setup of the DCB tests with falling-wedge impact tests

$$G_{IC} = \frac{3P\delta}{2b(a + |\Delta|)}, \tag{3}$$

where Δ is a crack length correction, which is obtained by generating a least-square plot of the cube root of compliance $C^{1/3}$ as a function of the measured crack length.

In the impact DCB tests, the variation of the load against crack propagation is different from the static-test value because of the dynamic effects [5, 9]. Therefore, G_{IC} intensely varies when Eq. (3) is used, and an accurate G_{IC} value cannot be evaluated. Replacing the load with the displacement and crack length using Eq. (2), the fracture energy can be represented as a function of δ and a;

$$G_{IC} = \frac{9EI\delta^2}{4b(a + |\Delta|)^4}. \tag{4}$$

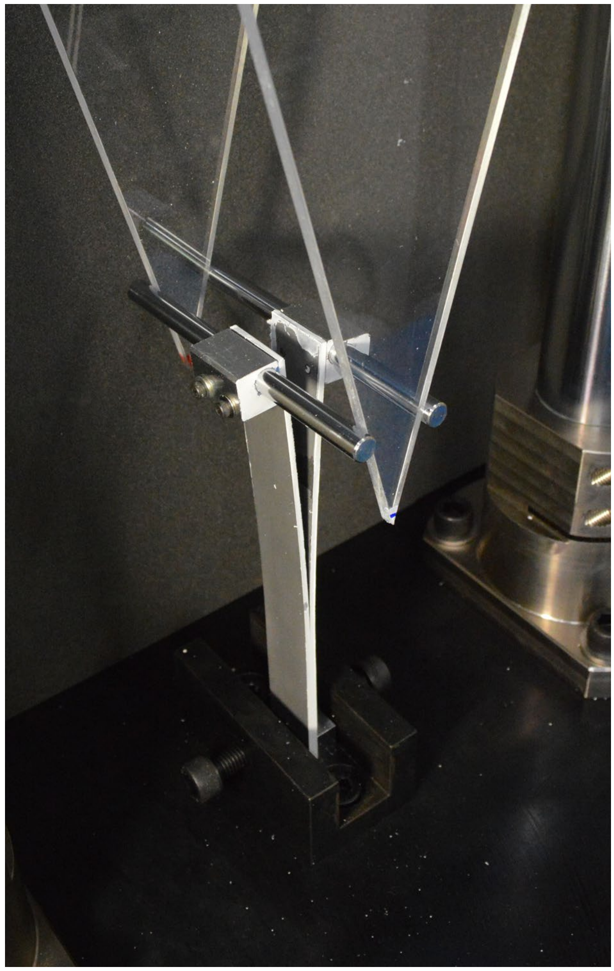

Fig. 4 During the test, the wedges descend and pass through the pins, which are inserted in fixed aluminum blocks at the end of the DCB specimen

We denote it as the load-independent method (LIM). Although the crack length correction cannot be used without measuring the load, it only depends on the elastic properties of the adherend [10]. Therefore, the calculated value of $|\Delta|$ from the average value in the quasi-static tests was applied to calculate the impact test results.

Experimental results and discussion

Figures 5 and 6 show the variation of the crack length with time under the quasi-static and impact condition. The crack propagation speed steadily decreases for the epoxy and polyurethane adhesives. The opening displacement speed under the impact condition was 1.84 and 1.90 m/s for the epoxy adhesive and polyurethane adhesive, respectively (Figs. 7 and 8).

Figure 9 shows the fracture energy of the epoxy adhesive in the quasi-static and impact tests. The average fracture energy was 283.1 J/m^2 for the quasi-static test with the CBT, 263.9 J/m^2 for the quasi-static test with the LIM, and 263.9 J/m^2 for the impact test with the LIM. Figure 10 shows the fracture energy of the polyurethane adhesive in the quasi-static and impact tests. The average fracture energy was 2475 J/m^2 for the quasi-static

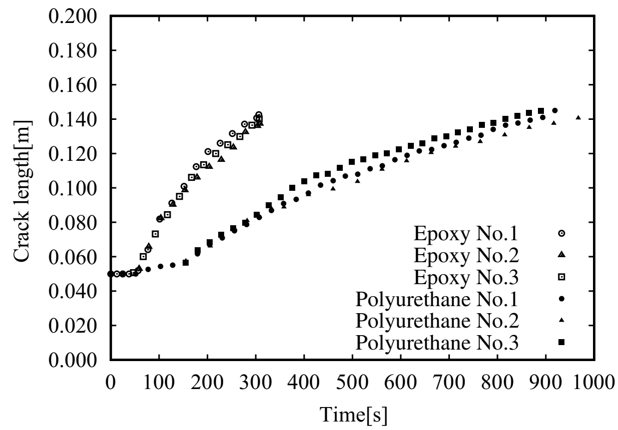

Fig. 5 Results of the crack length versus time under the quasi-static condition

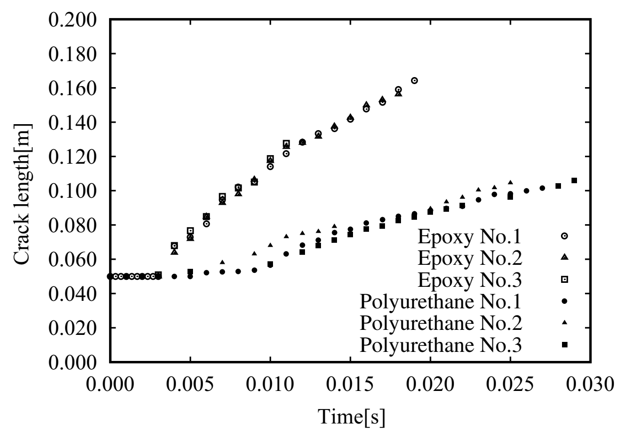

Fig. 6 Results of the crack length versus time under the impact condition

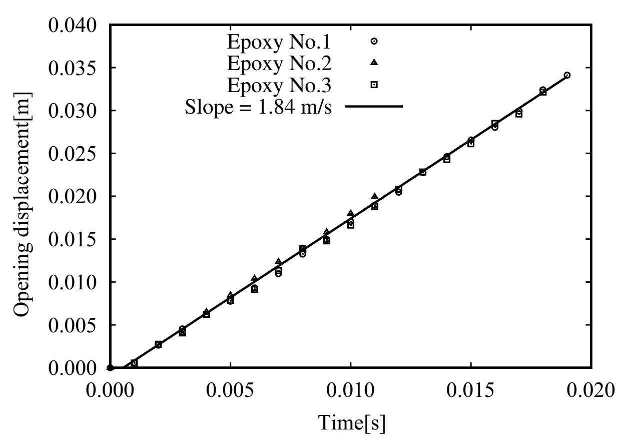

Fig. 7 Results of the opening displacement versus time for the epoxy adhesive under the impact condition

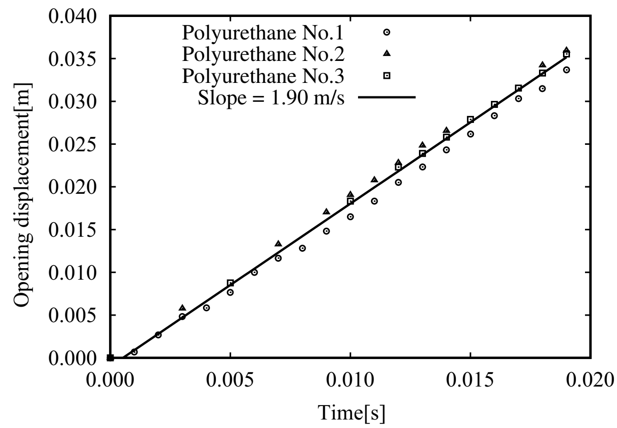

Fig. 8 Results of the opening displacement versus time for the polyurethane adhesive under the impact condition

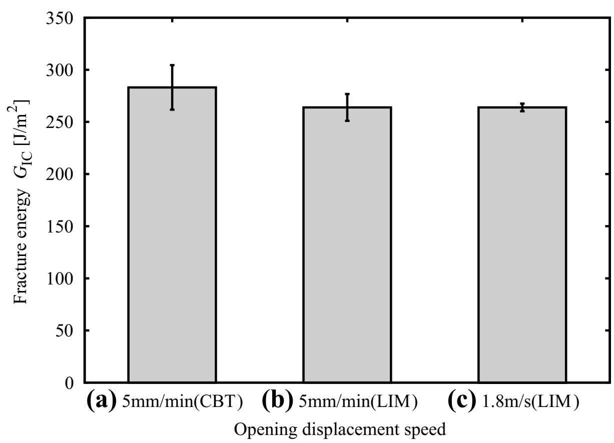

Fig. 9 Experimental results for the epoxy adhesive, which were calculated with: **a** CBT; **b** and **c** LIM

test with the CBT, 2733 J/m^2 for the quasi-static test with the LIM, and 4224 J/m^2 for the impact test with the LIM. Thus, the difference in G_{IC} value between the CBT and LIM under the quasi-static condition, which arises with the change of calculation methods [8, 11], was within the acceptable range for both adhesives. In contrast, the comparison of the results with different loading conditions indicates that there is a difference in rate dependence of the adhesive types. In the case of the epoxy adhesive, little difference in G_{IC} was observed because the T_g of the epoxy adhesive is much higher than the room temperature. In the viscoelastic material, the temperature and the loading speed have a negative correlation, and increase of the loading speed does not produce the state change of the material in the case of high T_g adhesives. Thus, the opening speed does not affect the G_{IC} value at room temperature. However, in the case of the polyurethane adhesive, the G_{IC} value for the impact test was approximately 1.5 times larger than that for the quasi-static condition. The high rate dependence on the strain rate was likely because of the ductile properties of the polyurethane adhesive, which is related to the lower glass transition temperature.

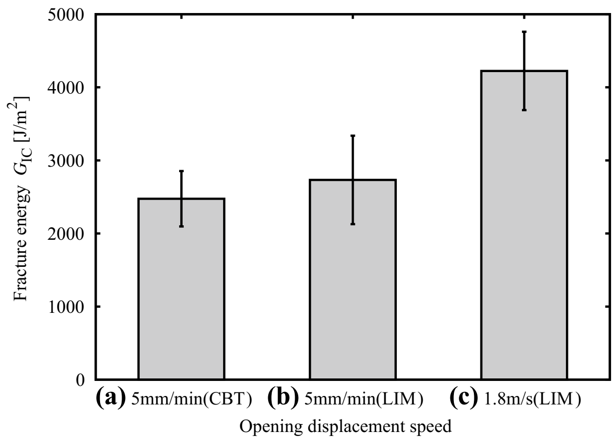

Fig. 10 Experimental results for the polyurethane adhesive, which were calculated with: **a** CBT; **b** and **c** LIM

Additionally, the calculation of G_{IC} without measuring the load ensures a profitable discussion of the rate dependency of mode I fracture. Symmetrical fractures of the DCB specimens were obtained with the falling-wedge impact test machine at the opening speed of approximately 1.8 m/s. Although a taller machine is required for the tests with faster opening speeds, this test method has a high potential for impact DCB tests with various types of adhesives.

Conclusions

In this study, DCB tests under the impact loading condition were conducted to evaluate the fracture energy G_{IC} in comparison with the results of the quasi-static condition. In the impact tests of the DCB specimens, a falling-wedge impact test machine was used to propagate the crack, and a high-speed camera was used to measure the opening displacement and crack length. The experimental results confirm that the fracture energy of the epoxy adhesive is independent from the strain rate. In contrast, the fracture energy of the polyurethane adhesive with impact loading is approximately 1.5 times larger than that with the quasi-static loading. Therefore, the experiment indicates that the fracture energy of the ductile adhesive is more likely affected by the loading condition than that of the brittle adhesive. In addition, the falling-wedge impact test machine can be used to evaluate the rate dependence in a wide range of fracture energy, including the structural adhesives.

Authors' contributions

YY performed the experiments and wrote the manuscript. XL performed the experiment for the polyurethane adhesive under impact loading. YS and CS helped to write the manuscript. All authors read and approved the final manuscript.

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Acknowledgements

This paper is based on the results from a future pioneering program commissioned by the New Energy and Industrial Technology Development Organization (NEDO). The authors would like to express their sincere appreciation to the project members who have provided valuable information and participated in useful discussions. They also wish to thank Sunstar Engineering Inc. (Japan) for the material supply.

Competing interests
The authors declare that have no competing interests.

Funding
New Energy and Industrial Technology Development Organization.

Received: 10 September 2016 Accepted: 22 February 2017
Published online: 28 February 2017

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