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Effect of high strain rate and low temperature on mode II fracture toughness of ductile adhesive

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ABSTRACT

Adhesive joints have a great potential use in different industrial applications which may encounter low temperature and high strain rate conditions, the fracture behavior of adhesive needs to be reliably predicted under such conditions. This paper experimentally studies the mode II fracture toughness of a polyurethane (PU) adhesive at room temperature (RT) under quasi-static condition with J-integral method and at low temperatures under high strain rate conditions with compliance-based beam method (CBBM), which does not need the observation of crack propagation. Typical R-curves of the PU ductile adhesive under the loading rate of 2 m/s, 3 m/s and at RT, −20°C, −40°C respectively are obtained. From the experimental results, low temperature and high strain rate has great effect on mode II fracture toughness of adhesive. The mode II fracture toughness of this PU adhesive decreases by at least one order of magnitude when conditions vary from quasi-static to high rate. Under the high strain rate conditions, the mode II fracture toughness of adhesive increases with the decrease of the temperature. At −40°C under the loading rate of 3 m/s, mode II fracture toughness of adhesive increases by 130% compared with the data at RT under the loading speed of 2 m/s. Through the experiment, the relationship between the mode II fracture toughness of adhesive, the nominal shear strain rate and the temperature is obtained. It is concluded that the mode II fracture toughness of adhesive at RT under quasi-static condition cannot be used to design and analyze adhesive joints at low temperatures under high strain rate conditions.

1. Introduction

The application of adhesive in structures is on a rise recently because of its excellent properties in joining dissimilar adherends, saving structure weight and reducing stress concentration in the structure. Adhesive joints have great potential use in different applications like aircrafts, aerospace and vehicles in which adhesive maybe subjected to short duration dynamic loadings and low temperatures [1,2]. As an important component of joints, it is critical to reliably predict the fracture behavior, including mode I and mode II fracture toughness of structural adhesive for the design of adhesively-bonded joints. Compared with mode I, there are very limited researches on mode II fracture toughness of adhesive due to the difficulty of observation the crack propagation in mode II fracture tests. Moura et al. [3,4] proposed a method, called compliance-based beam method (CBBM) to obtain the G_{IIC} without the need for observation the crack and can effectively account for the stress softening area at the crack tip, which is suitable for ductile adhesive. Azevedo et al. [5] studied the fracture toughness of three different adhesives and confirmed the correctness of the CBBM. Monteiro et al. [6] studied mode II fracture toughness of metallic adhesively-bonded joints and employed compliance calibration method (CCM), corrected beam theory (CBT) and CBBM respectively. The advantages and disadvantages of different methods were compared and the conclusion was drawn that the fracture toughness of adhesive calculated through these three methods was consistent. However, the CBBM also has its limitations, the results are unreliable when the adherends experience obvious plastic deformations [7]. It is necessary to use J-integral method to get mode II fracture toughness of the adhesive in this occasion. Walander et al. [8] used J-integral method to calculate the mode II fracture toughness of adhesive through smaller metallic steel-bonded joints when the steel underwent significant plastic deformation. The advantage of J-integral method is that it can use smaller specimen size to reduce the scale of the experiment and the difficulty of test, while avoiding the data analysis error caused by linear elastic fracture mechanics. Marzi et al. [9] studied the effect of adhesive thickness on mode II fracture toughness of epoxy and concluded that

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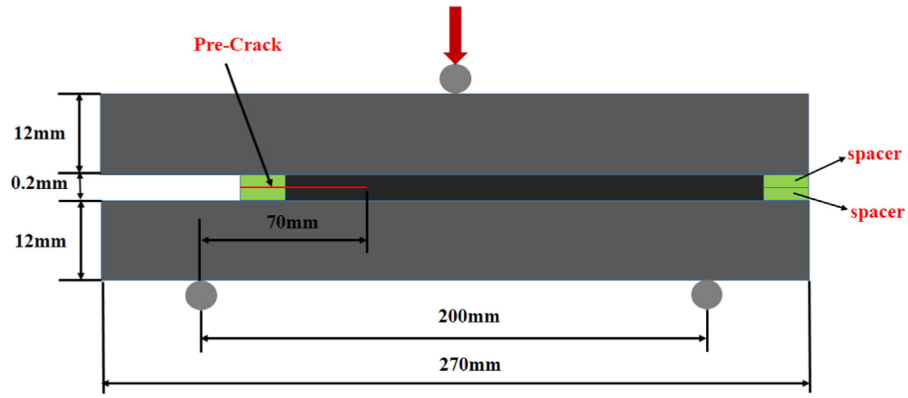

Fig. 1. Illustration of ENF specimen dimensions.

the fracture toughness increased with the increasing of thickness.

Several studies focused on mode II fracture toughness of adhesive at different temperatures. Banea [10] studied the fracture toughness of epoxy at high temperatures and used cohesive zone model (CZM) to simulate the whole experimental process. It was concluded that mode II fracture toughness of epoxy adhesive increased first and then decreased with the increase of temperature. When the temperature exceeded the glass transition temperature Tg of adhesive, mode II fracture toughness of adhesive decreased to almost zero. Walander [8] et al. investigated the relationship between CZM parameters and the environmental temperature, indicating that mode II fracture toughness, cohesive strength and stiffness decreased with the increase of temperature. At 80 °C, mode II fracture toughness reduced by 2/3 compared to the data at -30 °C. Similar to the study on mode I fracture toughness, research on temperature dependence of mode II fracture toughness is mainly concentrated on high temperature range. The research on low temperature effect is much less.

Carlberger et al. [11] studied the cohesive parameters of epoxy adhesive at different strain rates (10^{-4} /s-10/s) and established the relationships between the mode II fracture toughness and strain rate. The mode II fracture toughness of this specific adhesive decreased with the increase of the strain rate. Blackman et al. [12] used a drop-weight impact machine to study the dynamic mode II fracture toughness of adhesives under different loading rates. In the experiment, the deformation of specimens was recorded by high-speed camera to determine the initiation time of crack. It was concluded that mode II fracture toughness of adhesive was inversely related to the strain rate. Sun et al. [13,14] studied the mode II critical strain energy release rate of adhesive under low-speed impact loadings. Unlike mode I, mode II crack propagation did not show any transition from ductile to brittle under impact loading. The critical strain energy release rate and cohesive strength increased with the increase of the strain rate, but the rate of increase was not large. Brambleby [15] studied the effect of loading rate on mode II fracture toughness of glass fiber reinforced composites. With the increase of loading rate, fracture toughness increased at the maximum loading rate of 6000 mm/min. Xu et al. [16] studied the mode II fracture toughness of steel at different strain rates and pointed out that strain rate sensitivity of the same material varied with different loading rates. Under different loading rates, the fracture toughness trend of increasing or decreasing even reversed. It has been confirmed in the study of mode I fracture toughness, but it is seldom reported in the study on mode II dynamic fracture toughness. Li et al. [17] reviewed different experimental methods to test fracture toughness of material under dynamic loadings and loading rate effect on fracture toughness.

For the study on mode II fracture toughness of adhesively-jointed structures, most of them adopt the method of linear elastic fracture mechanics. There is no uniform trend in the study on the effect of loading rate on mode II fracture toughness. Wade and Cantwell [18] studied the effects of loading rate and the environmental temperature on the fracture toughness of adhesive and illustrated that the mode II critical strain energy release rate was very sensitive to both. The mode II fracture toughness reduced by 50% when the temperature increased to 60 °C and it increased by 1.5 times at high loading rate.

As macromolecule material, the fracture toughness of adhesive is sensitive to high loading rate and low environmental temperature. Their combined effect on mode II fracture toughness of adhesive is rarely studied and the existing study mainly focuses on high temperature and relatively high loading rate which actually belongs to quasi-static condition. In this paper, the mode II fracture toughness of ductile polyurethane adhesive under quasi-static condition at room temperature (RT) and under different loading rates (2 m/s and 3 m/s) at low temperatures (-20 °C and -40 °C) is studied experimentally, and its variation with low temperature and high strain rate is obtained.

2. Experiment

2.1. Sample fabrication

The polyurethane (PU) adhesive used in this paper was Ashland Pliogrip 7705b, a two-component adhesive with the glass transition temperature of 45 °C. The viscosity of the adhesive is 30,000 mPa•s and the cure condition for this adhesive is 23 °C for 45 min, according to the manufacturer of adhesive. This adhesive is ductile at RT and widely applied in automobile industry.

The mode II fracture toughness of the adhesive at different temperatures under different strain rates was measured using the End-Notched Flexure (ENF) specimens and the specific dimensions were shown in Fig. 1. Stainless steel with the width of 12 mm was adopted for the adherends and the thickness of adhesive was 0.2 mm. The ENF joint surfaces were blasted with #220 sandpaper, degreased with acetone and then soaked in a sodium hydroxide solution with a concentration of 20% for 30 minutes. After soaking, it was rinsed with acetone and distilled water. To control the thickness of adhesive, four 0.1mm-thick spacers, two on each side, were inserted between the adherends before the application of adhesive, as shown in Fig. 1. A sharp pre-crack with the length of 70 mm was fabricated by a 40 μm thick polytef (PTFE) film. The pre-crack was placed in the middle of the spacers to ensure that the pre-crack positions in the mid-plane of adhesive. The spacers were removed after the joints being cured. The ENF joints were cured at RT for 45 min. After curing, scrape the excess adhesive on the side of joints to complete ENF specimen preparation.

2.2. Test procedure and data analysis

The commercially available FEA software Abaqus 6.14 was employed to simulate the fracture behavior of ENF specimen under quasi-static conditions at RT before experimental testing. It can be seen that