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Tensile properties of a polymer-based adhesive at low temperature with different strain rates

Zhemin Jia [a], Guoqing Yuan [a, *], Hei-lam Ma [c], David Hui [b], Kin-tak Lau [c]

[a] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai, 200092, China
[b] Department of Mechanical Engineering, University of New Orleans, New Orleans, LA 70148, USA
[c] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, Hung Hom, Hong Kong Special Administrative Region

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The tensile properties of a polymer-based adhesive subject to different strain rates at low temperature were investigated. Experimental results showed that the strength of adhesive increased remarkably with the increase of strain rate and decrease of temperature. According to the results, the strength of adhesive at low temperature (−40 °C) and high strain rate increases as compared with that at room temperature and the same strain rate. The effect of strain rate and low temperature on strength of adhesive is not simply superimposed. Meanwhile the coupling effects on strain rate and low temperature to the tensile strength, failure strain, Young's modulus, and fracture energy are also discussed in this paper. A constitutive model of adhesive at high strain rate and low temperature is proposed.

1. Introduction

Adhesive bonding has been applied in a wide range of fields such as aerospace and automobile industries due to its ability of effectively reducing structural weight, producing more uniform stress distribution in connection parts as compared with other fastening systems, and connecting dissimilar adherends in particular [1]. The properties and bonding capability of adhesives at low temperature conditions have attracted tremendous attention recently, as the demands for its applications in harsh environments are increasing [2–4]. As an example, an automotive body, with the exception of its engine, may undergo a crucial temperature ranging from −40 up to 125 °C in various working conditions [5]. Under this temperature range, the properties of adhesive may vary and such effects should be considered properly at the design stage of vehicles. Banea et al. [6] have studied the tensile properties and mode I toughness of an epoxy adhesive at high temperature condition. Their results showed that the tensile properties and toughness of the adhesive were affected by high temperature, particular close to its glass transition temperature (Tg). Melcher et al. [7] have explored the Mode I fracture toughness of adhesively bonded composite joints at cryogenic temperature and compared with that measured at room temperature (RT) condition. Interestingly, nearly 50% reduction of the adhesive fracture toughness at cryogenic temperature was shown.

The impact load is another important parameter when designing adhesive bond joints for the automotive industry as required in the safety rules for passengers and quality norms for manufacturers [8]. By considering the car crashworthiness, it is reported that the maximum strain rate of substrates may reach 200/s, the strain rate for adhesive can be even higher [5]. Commonly, adhesive is fabricated by using various kinds of polymers, which is composed of a large number of long-chain molecules with different conformations. The long-chain molecules are stretched when bearing an external force and their reaction time is largely reduced with the increase of stretching rate, leading to strain rate sensitivity of adhesive. As an important structural component, the strain rate sensitivity of adhesive can significantly affect the strength and the failure modes of an entire bonded structure when the loading rate is different from the quasi-static condition [9,10]. Split Hopkinson Bar is a commonly-used equipment for testing the dynamic properties of materials at high strain rates ranging from 10^3/s to 10^5/s [11–13]. For instance, Iwamoto et al. [14] and Goglio et al. [15] investigated the compression stress–strain curves of two structural adhesives at the strain rate of 10^3/s on compressive split Hopkinson Bar. The available data for compression are more than that of tensile data as the Hopkinson bar was at first developed for compression tests instead of tensile

* Corresponding author.
E-mail address: 90020@tongji.edu.cn (G. Yuan).

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tests. Until recent years, the experimental set-ups for tensile, bending and torsion have been developed [15]. Goglio et al. [15] and Liao et al. [16] have studied the dynamic tensile properties of two-part epoxy adhesives through the tensile split Hopkinson bar. Takiguchi et al. [17] have researched the relationship between the shear deformation and the strain rate, and proposed viscoelastic constitutive model to describe the variation of strain rate sensitivity in different strain rates.

Apart from the individual effect of temperature or strain rate, efforts have been made to study the combined effects of temperature and strain rate on the adhesive properties. Carlbergeret et al. [5] experimentally studied the effects of temperature and strain rate on the cohesive properties of adhesives. The dependencies of the fracture toughness and peel-off strength on temperature and strain rate were focused. Banea et al. [18] have studied the tensile properties of an epoxy adhesive from RT to 150 °C and under the relatively low loading rate in the range of 0.1–10 mm/min. Adamvalli et al. [19] have investigated the dynamic shear strength of an epoxy adhesive at high temperatures using the Hopkinson bar with an environmental chamber. Chai [20] has researched the layer thickness, strain rate and temperature influence on the shear deformation and fracture under shear load. Though there are several researches on strain rate and temperature effect on the properties of adhesive, data about the coupling effect of low temperature and high strain rate on mechanical properties of adhesive have not yet been available.

Meanwhile, models to describe the effect of strain rate and low temperature on the effective stress of adhesive are rare. The constitutive equations to describe the stress of adhesive at various strain rates and low temperatures are important not only to understand the effect of strain rate and low temperature on mechanical properties of adhesive but also could be used as accurate input parameters for Finite Element Analyses conducted by using commercial packages, like ANSYS or ABAQUS [21,22]. Zubaidy et al. [9] have proposed the empirical constitutive equations to illustrate the relationship between the dynamic strength and static strength in the corresponding medium strain rate range. A three-dimensional constitutive model has been derived by Iwamoto et al. [14] to describe the dynamic compressive strength at high strain rate. Goglio et al. [15] have proposed a poly-linear fit to reveal the influence of strain rate on the dynamic strength of adhesive.

To select the proper adhesive for extreme conditions, like at high strain rate and low temperature, there are requirements to test the adhesive at the corresponding operating environment in advance. In this paper, the effect of strain rate and low temperature, along with their coupling effect on tensile properties of adhesive are investigated to provide the foundation data for designing and the analysis of adhesive bond joints. The adhesive samples were tested at various temperatures including RT, -20 °C and −40 °C with different strain rates through the universal testing machine and the tensile split Hopkinson bar both incorporated environmental chambers. The coupling effects on high strain rate and low temperature to mechanical properties of adhesive are also discussed. The dependencies of strength, failure strain and fracture energy on strain rate and low temperature are investigated. The strength of adhesive at high strain rate and RT increases more than two times compared with the measured at quasi-static condition and the same temperature and the failure mode turns into brittle at high strain rate. The low temperature has a similar impact on the mechanical performance of the adhesives. However, their coupling effect on tensile properties of adhesive is not as simple as expected. In this case, the effect of strain rate is counteracted by the effect of low temperature. A constitutive model that describes the dependency of effective stress on strain rate and low temperature is proposed.

2. Experimental

2.1. Sample fabrication

The adhesive used in this project was Ashland Pliogrip 7779, a two-component polyurethane (PU) adhesive with the glass transition temperature of 45.5 °C.This adhesive is widely used in the automobile industry for connecting composite materials. The viscosity of the adhesive is 30,000 mPa s at RT and the cure condition for this adhesive is 23 °C for 1 h.

A static mixer fabricated by a two-component caulking gun was used to mix the adhesive to minimize the production of voids. The mixture was then poured into a metallic mold according to French Standard NF T 76–142, as shown in Fig. 1 [23]. The silicon plate highlighted in Fig. 1 was used to control the thickness of adhesive plate and also prevent the leakage of polymer during curing process. The vacuum hot press was employed to generate a vacuum environment where a 2 MPa pressure could be applied on the working area of the metallic mold. After curing for 1 h at ambient temperature, the metal frames were unbolted and an adhesive sheet with the dimension of 235 mm × 90 mm was produced.

The dog-bone specimens were manufactured from the as-produced adhesive sheet according to GB/T2567-2008 and the detailed geometries were shown in Fig. 2(a). The thickness of the specimen was 2 mm. Much smaller dog-bone specimens were used in this study for Hopkinson tensile test, which were machined from the adhesive sheet with the thickness of 3.5 mm, as shown in Fig. 2(b). Specimens with the same size were used for both RT and low temperature tests.

2.2. Test procedure

2.2.1. Tensile test for quasi-static condition

The quasi-static tensile tests were conducted in a universal testing machine (Zwick 8406) at a constant crosshead rate of 2.0 mm/min in Fig. 3. The load cell of the machine was 30 KN. The automatic clip-on extensometer with the gauge length of 50 mm was used for strain measurements. For the low temperature (−20 °C and −40 °C) tests at quasi-static condition, an environmental chamber was employed to achieve the desired temperature. The specimens were kept in the chamber for at least 10 min to reach the temperature equilibrium. At least four specimens for each temperature were tested.

2.2.2. Tensile test for high-strain rate condition

Split Hopkinson bar was used to test the adhesive at high strain-rate. The schematic diagram of tensile Hopkinson bar was shown in Fig. 4.

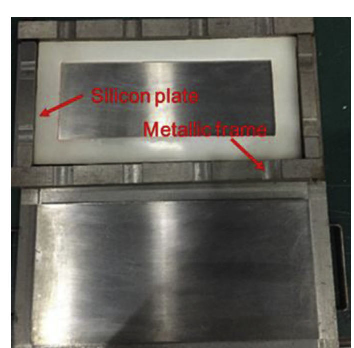

Fig. 1. Metallic mold for manufacturing the adhesive sheet.