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Predicting impact shear strength of phenolic resin adhesive blended with nitrile rubber

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ABSTRACT

The impact shear strength of phenolic resin adhesive blended with nitrile rubber in a double-lap steel joint was measured to discuss the applicability of the strain rate-temperature equivalent principle. This strain rate-temperature equivalent principle was confirmed to be applicable to the quasi-static shear strengths of the adhesive. Because phenolic resin adhesive blended with nitrile rubber was in the glass transition state under a quasi-static deformation at room temperature and its adhesive strength was sensitive to the strain rate, the impact strength of the adhesive could not be predicted without the strain rate-temperature equivalent principle. Instead, the impact strength of the adhesive measured by using a manufactured impact testing machine could be predicted approximately with quasi-static results at low temperature by using the principle. The strain rate-temperature equivalent principle was clarified to be sufficient for predicting impact strengths without the need for impact testing.

1. Introduction

Adhesive bonding is applied to joint structural components in several mechanical structures. The strengths of adhesive joints are important to ensure the reliability of structures [1]. Because, in many cases, this bonding is subjected to impact loads, the impact strength of the adhesive also needs to be evaluated. Several researchers clarified the impact strengths of adhesive joints by using a split Hopkinson pressure bar testing [2–9]. Some researchers have clarified the strengths by using drop weight testing and pendulum testing [10–15].

The dependences of high strain rates on adhesions were discussed in almost all pieces of research related to impact strengths. Temperature dependence needs to be considered because of thermo-viscoelasticity in polymer bonds as well as strain rate dependence on the impact strengths of adhesive joints, [16,17]. The dependences of strain rates and temperatures on deformation are known as the temperature-time equivalent principle in thermo-viscoelastic theory [18,19]. The strengths and fracture toughnesses of many polymers were clarified to be governed by this principle in several pieces of research [19–30]. Some studies have shown that the principle can be applied to adhesive joints or bonds. Gent and Petrich [31] clarified that the peel energy of styrene-butadiene rubber adhesives on a polyester film followed the time-temperature equivalent principle above the glass transition temperature with the Williams–Landel–Ferry (WLF) equation [18,19]. Gent and Kinloch [32] expressed adhesive fracture energy as a function of temperature and deformation rate of copolymer of butadiene and styrene/mylar-coated steel joints on the basis of the strain rate-temperature equivalent principle with the WLF equation. Aubrey and Sherriff [33] investigated the peel adhesions of mixtures with various proportions of natural rubber and each of two tackifier resins, a poly-β-pinene and a modified pentaerythritol rosin ester, in joining a flexible polyester strip to a plane glass substrate and confirmed that the time-temperature equivalent principle could be applied to the adhesion. Lim and Mizumachi [34,35] investigated the critical mode I and II strain energy release rates of polyurethane adhesives between Japanese birch plates. They reported that master curves based on the rate-temperature equivalent principle could be applied to the critical strain energy release rates. Derail et al. [36,37] reported the peeling properties of polybutadiene/tackifying resin compatible blends and found the master curve of the peeling force. Guiu and Shanahan [38] used a peel test to investigate adhesion between high-density polyethylene (HDPE) with an inner layer of an ethylene/vinyl alcohol copolymer (EVOH) in a five-layer structural system that consisted of two outer strata of HDPE with an inner layer of EVOH. They found that the strain rate- and temperature-dependences of peel energy can be described by using a

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time–temperature superposition with an Arrhenius-based relation [18,19]. As described above, the report on the time-temperature equivalent principle was limited to the static and quasi-static strengths of the adhesives. However, the impact strengths of adhesive joints determined on the basis of time-temperature superposition have not been discussed. The applicability of the time-temperature equivalent principle to impact strengths needs to be considered to predict impact strengths from static ones under a different temperature environment because a specific apparatus is required to measure the impact adhesive strength and managing the deformation rate is not easy in impact testing.

We describe how the impact shear strength of phenolic resin adhesive blended with nitrile rubber in a double-lap joint was measured to discuss the applicability of the strain rate-temperature equivalent principle. Quasi-static tests were done at different strain rates under several temperatures to draw a master curve of the shear strength on the basis of the strain rate-temperature equivalent principle. Impact tests were conducted by using a manufactured pendulum testing machine to measure strengths under high strain rates. On the basis of a comparison of the impact shear strengths with the quasi-static strengths on the master curve, the prediction of the impact strength of the adhesive was discussed.

2. Specimen preparation

Simple double-lap joints with phenolic resin adhesive blended with nitrile rubber were prepared to measure the shear strength of the adhesive without deformation caused by a specimen bending. The joints consisted of three steel plate adherends having 10 mm in overlap length, and their geometric configuration is shown in Fig. 1. The specimens for impact tests had holes near both ends to fix them to the impact testing machine explained in Section 3, although specimens for quasi-static tests did not. The distance between the hole and the adhesive region was lengthened in order to average stress dispersed due to the holes on the basis of the dynamic stress concentration around a hole [39]. The Young's modulus, yield stress, and ultimate tensile strength of the steel were 211 GPa, 261 MPa, and 349 MPa, respectively. Surfaces of the steel adherends were treated by shot-peening to increase adhesive strength. The average surface roughness after the shot-peening was 7.4 μm. The adherends were bonded with resin adhesive under a pressure of 2.5 MPa and at a temperature of 503 K for 30 min. Several prepared specimens were cut after bonding to measure the thickness of the adhesive layer between the steel plates with a scanning electron microscope (JSM-T200, Jeol). The average thickness of the adhesive layers was 30 μm.

3. Experimental procedure

3.1. Quasi-static test

Quasi-static tests were conducted by using a tensile testing machine (8501, Instron) with tensile displacement rates of 0.01, 1, and 100 mm/min for each temperature of 203, 223, 253, 293, 343, and 423 K in a thermostatic oven (3119-007, Instron). The total test conditions were 18 combinations of 3 displacement rates with 6 temperatures. Ten specimens at the standard condition, a displacement rate of 1 mm/min and room temperature of 293 K, were measured, though one specimen for the other conditions was measured. The load was measured with a load cell in a testing machine, and deformation of the specimens was also measured in a gage length of 25 mm by using an extensometer (Fig. 2). The deformation included deformations of the adhesive and the adherends. Because the loading at the breaking of the resin adhesive was below the yielding of the steel adherends, the elastic deformations of the adherends were eliminated from the measured deformation in the gage length to evaluate the deformation of the adhesive layer. The average shear stress, which was the tensile force divided by the initial overlap area, was used to express the strength of the joints. The average shear strain rate was defined as the ratio of the deformation rate of the adhesive layer and the average thickness of the adhesive.

3.2. Impact test

(a) Impact testing machine

An impact testing machine was developed to measure impact shear strength, as shown in Fig. 3(a). The machine had a pendulum and an impactor. The impactor consisted of two steel bars that were 25 mm wide, 30 mm high, 300 mm long, approximately 0.7 kg in weight, and were rounded at the collision ends. The right side of each specimen was mounted at the left end of a dynamic load cell, shown in Fig. 3(a). The left end was connected by pins at Block D, which moved freely on a steel base. The right end of the dynamic load cell was fixed through Block E on the steel base. The impactor was collided to the Block D to apply impact tensile load to the specimen. Two strain gages (KFG-2-120-C1-11, Kyowa) were attached on both sides of Adherend A to confirm that the strain histories measured from the strain gages coincided by simultaneously colliding the two bars of the impactor to Block D (Fig. 1). The impact tests were conducted at room temperature, 293 K. Because the overlap length of the specimen was 10 mm, stress distribution in the adhesive region could be

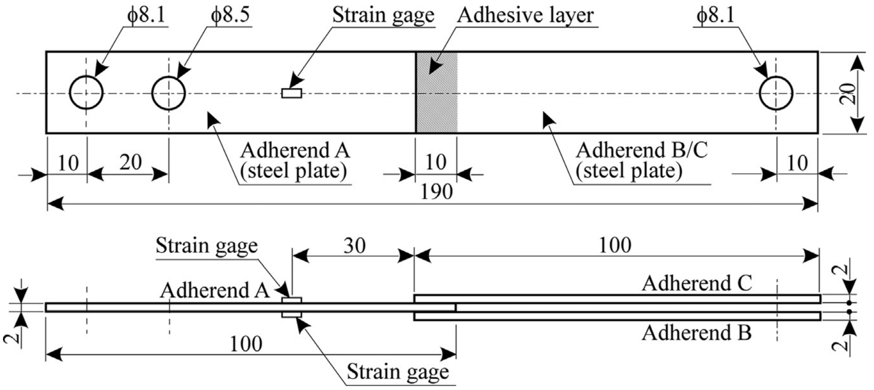

Fig. 1. Specimen. All dimensions are in mm. Specimens for impact tests had holes near both ends to fix them to impact testing machine, although specimens for quasi-static tests did not. Two strain gages on both sides of Adherend A were used in impact test to confirm simultaneous collision of two bars in impactors.