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FURTHER STUDY ON THE EFFECTS OF SUBSTRATE MATERIAL AND JOINT GEOMETRY ON THE QUASI-STATIC BEHAVIOR OF ADHESIVE JOINTS

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ABSTRACT

A series of quasi-static fracture tests have been carried out on double-cantilever-beam (DCB) specimens in order to validate the differences in the previously measured values [1] of critical energy release rate (G_c) for aluminum and steel adhesive systems. In this new study, the testing machine was modified and a crack detection program was used in order to minimize the operator interference. The results from this study indicated that there is no significant substrate material or joint geometry effect on the measured values of G_c. The *R*-curves of both adhesive systems were almost identical when the strain rates in the adhesive layers of DCB's were maintained the same. After each fracture test, the locus of joint failure was examined optically and the degree of interfacial failure was determined by image processing software. Only a minor mismatch of the *R*-curves was detected, which is probably related to different test system response to unequal load levels, the degrees of interfacial delaminating, the stress field around the crack tip, and perhaps the size of the damage zone ahead of the crack.

Keywords: Adhesive joints, substrate material dependency, joint geometry, toughened-epoxy, quasi-static fracture test

INTRODUCTION

The results of a previous study [1] showed that G_c appeared to depend significantly on the substrate material and the adherend thickness. Similar differences have also been reported by others. Bell *et al.* [2] found the highest values of G_c associated with joints having stiffer adherends; however, Yan *et al.* [3] reported that G_c was lower for stiffer substrates. These observations were attributed to changes in the stress field ahead of the crack [2] and the degree of triaxiality of the stress state [3]. In a more recent study, Blackman *et al.* [4] reported a minor mismatch in fracture test results on aluminum and steel adhesive systems. Considering the different observations, the objective of the present study was to validate the differences previously observed in the measurements of G_c for aluminum and steel adhesive systems.

EXPERIMENTS AND ANALYSIS

In this work, aluminum (6061-T6 and 7075-T6) and steel (AISI 1018 and 4140) bars with different thicknesses were bonded with a 0.4 mm thick layer of toughened heat-cured epoxy adhesive, used in the automotive industry. More details of surface preparation technique and the joint fabrication procedure can be found in Ref. [1]. The only difference between the surface preparation technique and joint fabrication procedure used in Ref. [1] was that in the present study, the sides of the specimens were gently sanded and cooled repeatedly in order to minimize the effects of finishing work. In order to eliminate sources of possible errors, the testing machine was modified by replacing the fixed end support with a four-roller system as shown in Fig. 1(a). For minimizing the operator interference, the testing machine was also programmed for crack detection via the variation of joint compliance, Fig. 1 (b). The program was initially calibrated by using an optical system mounted on a linear stage for monitoring crack propagation. Most of the tests were conducted under mode-I loading where the greater difference in measured values of G_c was observed in the first study [1]. The variation of opening elastic strain rate versus crack length was also determined from the finite element analyses for aluminum and steel DCB specimens, Fig. 2. It was found that the bondline strain rate was directly dependant on the pin load rate. In each loading step, therefore, the machine operated under displacement control with a variable crosshead speed, in order to maintain the loading rate constant at 10 N/s. This ensured that the bondline strain rates of the steel and aluminum adhesive systems were kept at the same level for all crack lengths. During each load step, the machine automatically controlled the variation of joint compliance and stopped moving if the magnitude of the second derivative of joint compliance exceeded a very small positive threshold, as shown in Fig. 1(b) within the dashed circle. The crosshead was then stopped for 30 seconds to let the crack propagate for a few millimeters. The crack propagation and the drop in load within this time period were considered as an evaluation index for controlling the overshoot in loading. After each fracture test, the locus of joint failure was optically examined and the degree of local interfacial failure was determined by using image processing software. Typical results are shown in Fig. 3 for aluminum and steel DCB's having different thicknesses and tested under mode-I loads. Ignoring the normal scatter in test data, no significant material dependency was observed in G_c measurements.

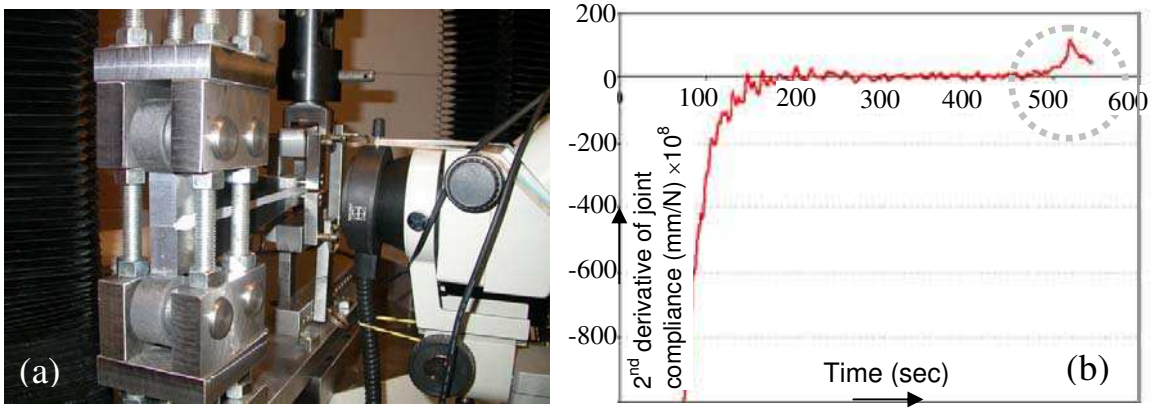

Fig. 1) Test setup and procedure (a) Roller end-support of quasi-static test setup, (b) Variation of joint compliance index with loading time.

The slope of the rising part of the R-curve reflects the crack propagation distance required to establish a fully developed damage zone. Hence, Fig. 3 shows that the development of the damage zone was similar in aluminum and steel DCBs tested at similar loading rates. Similar conclusions were also reached for the tests at the higher phase angles; however, the rising parts in the latter case were slightly longer than in mode-I loading. From the test results, the fracture envelope of both systems was determined by using both a beam theory [5] and the beam-on-elastic-foundation model [6], Fig. 4. A series of finite element analyses (FEA) were also performed to gain a better understanding of the effect of the substrate material on the value of G_c. From the FEA models, the stress field and the size of the plastic zone ahead of the crack were found to depend slightly on the joint geometry; however, the calculated values of G_c for both adhesive systems were almost identical.

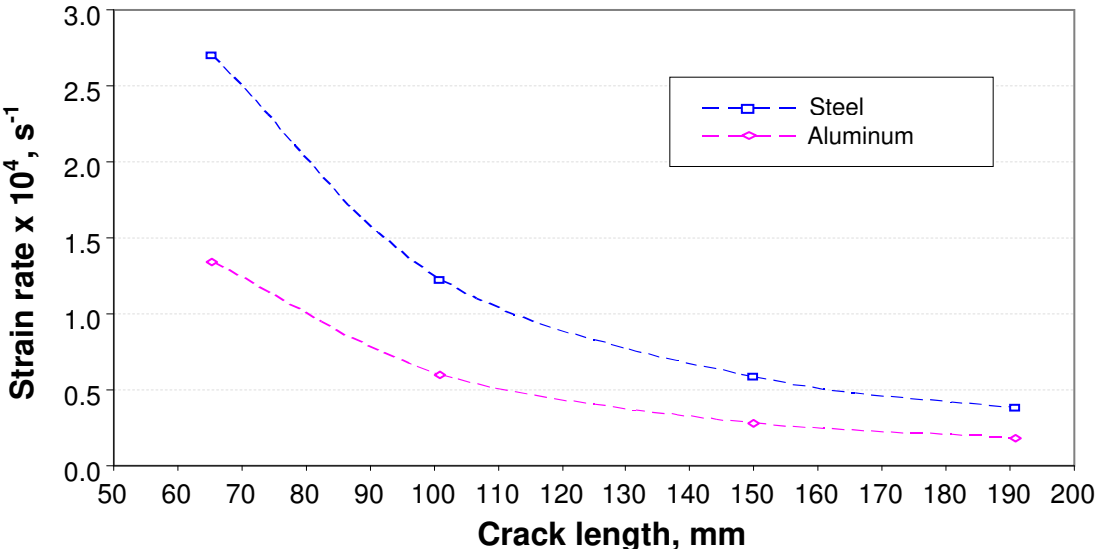

Fig. 2) Opening strain rate in the bondline of aluminum and steel systems calculated from 2D finite element analyses for a pin opening speed of 1.0 mm/min.

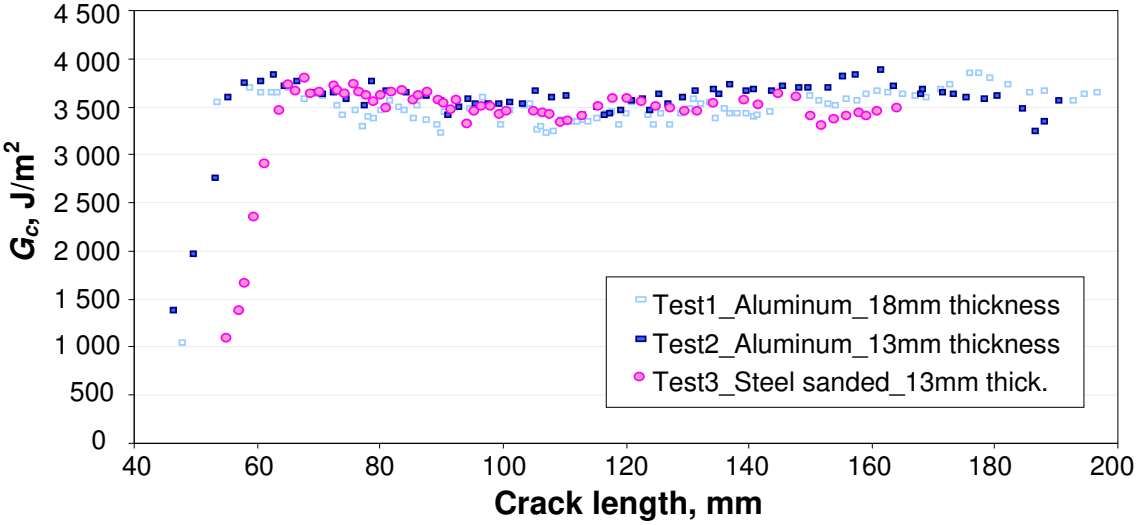

Fig. 3) Mode-I R-curves for aluminum and steel adhesive systems having different adherend thicknesses.

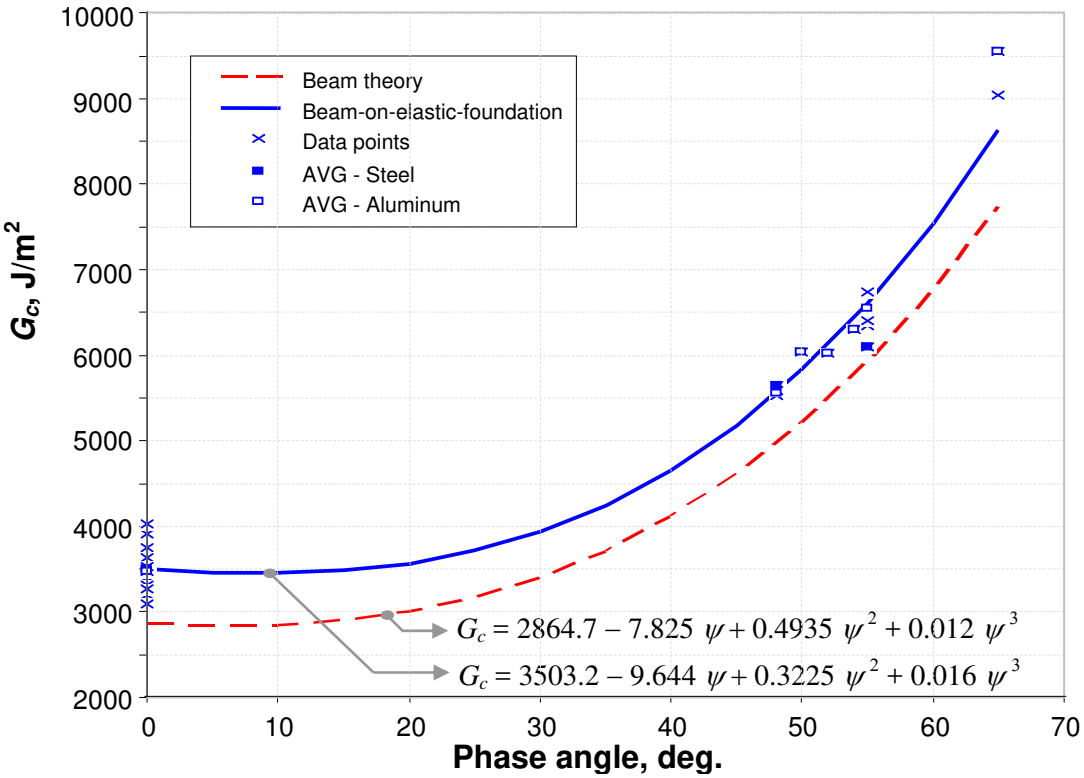

Fig. 4) General fracture envelope of aluminum and steel systems based on beam theory and beam-on-elastic-foundation model.

CONCLUSION

The new series of fracture tests on aluminum and steel adhesive systems revealed that the R-curves of both adhesive systems in cohesive failure were almost identical. Thus, this implies that the measurement of G_c becomes independent of substrate material and joint geometry when the testing parameters like load rate, crack advancement, and the load drop in each loading step were carefully controlled. The possible mismatch can then be related to the degrees of interfacial debonding and different machine response to unequal load levels.

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