International Journal of Adhesion & Adhesives 60 (2015) 16–22

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Prediction of the macroscopic fracture toughness of a composite/adhesive interface with periodic surface microstructures

Takuya Suzuki [a], Ryosuke Matsuzaki [b,*], Akira Todoroki [c], Yoshihiro Mizutani [c]

[a] Structural Strength Department, Research Laboratory, IHI Corporation, 1 Shin-nakahara-cho, Isogo-ku, Yokohama, Kanagawa 235-8501, Japan
[b] Department of Mechanical Engineering, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan
[c] Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8552, Japan

ARTICLE INFO

Article history:
Accepted 26 February 2015
Available online 14 March 2015

Keywords:
Interface
Composites
Surface modification
Fracture mechanics
Nanoimprint lithography

ABSTRACT

We developed a formula for predicting the macroscopic fracture toughness of a composite/adhesive interface with periodic surface microstructures. The formula is an expression of the total energy consumption along the interface averaged by the macroscopic crack length. The formula takes the effect of the crack kinking energy into consideration to compensate for the difference between the otherwise predicted consumed energy and that determined by finite element (FE) analysis. The predictions of the developed formula indicate that the macroscopic fracture toughness increases with increasing aspect ratio and decreases with decreasing height of the microstructures, which is in agreement with the findings of our previous studies on crack growth analysis using a cohesive zone model. The validity of the formula was investigated using microstructures of various shapes and sizes, and good agreement was observed between its predictions and the results of FE analyses.

1. Introduction

Adhesive bonding is widely used in the joints of composite materials because it enables weight reduction, produces less stress concentration, and prevents galvanic corrosion compared to mechanical joints [1–3]. To obtain high adhesive bonding strength, appropriate surface modification is required, such as sanding using emery paper, sand blasting, chemical etching, and plasma etching. In sanding and sand blasting, the surface layer with a weak adhesive force is mechanically removed to increase the effective adhesive area and expose the inner surface with its high surface free energy [4]. In plasma etching, the surface is chemically modified [4].

Several studies have been conducted to investigate the relationship between surface roughness and bonding strength. For example, Critchlow and Brewis [5] applied grit blasting to the surface of an aluminum joint and concluded that a rougher surface did not improve the durability of the joint. Harris and Beevers [6] investigated the effect of different alumina grits on surface properties, and concluded that a rougher surface improved the durability of steel joints, which was attributed to the changes in the chemical and physical conditions of the surface. Shahid and Hashim [7] revealed that the roughness produced by grit blasting improved the strength of cleavage joints. These studies, however, investigated the effects of the surface morphology on the joint strength using randomly patterned surfaces achieved by grit blasting, and the specific effects of the surface profiles were not considered.

Conversely, some studies have investigated the effect of periodic surface microstructures on macroscopic fracture toughness. Rider and Arnott [8] introduced triangular microstructures to the surface of an aluminum adherend by milling, which produces less change in the chemical condition. They concluded that the increase in the base angle of the triangular microstructures improved the macroscopic Mode I fracture toughness, which was obtained by introducing local Mode II crack propagation. Kim et al. [9] studied the effect of periodic microstructures with half-circle cross sections on the macroscopic Mode II fracture toughness, and found that the toughness was increased by the cohesive fracture of the adhesive. Zavattieri et al. [10] used finite element (FE) analysis to investigate the effect of periodic microstructures with sinusoidal cross sections on unstable crack propagation, and determined the relationship between the aspect ratio of the sinusoidal curve and the unstable behavior of the crack propagation.

However, surface modifications such as sand blasting, plasma etching, and milling increase the material production processes because they are done after the composites have been cured. Moreover, the dust discharged during sanding and the chemicals used pollute the work environment. The application of these techniques to large adhesive areas such as aircraft structures is

---

* Corresponding author. Tel./fax: +81 4 7124 1501.
E-mail address: rmatsuza@rs.tus.ac.jp (R. Matsuzaki).

http://dx.doi.org/10.1016/j.ijadhadh.2015.03.003
0143-7496/

Table of nomenclature

A	aspect ratio of microstructures
h	height of microstructures
w	width of microstructures
s	position along the interface in the O-s coordinate system
Ψ	phase angle
G_i (i=I, II)	energy release rate in Modes I and II
$G_{ic,\text{int}}$ (i=I, II)	interfacial fracture toughness in Modes I and II
$G_{c,\text{int}}$	energy required for crack propagation along an interface
$G^0_{C,\text{ int}}$	macroscopic fracture toughness
l	crack length along an interface
G^A_C	modified macroscopic fracture toughness
W_c	deviation of the energy release rate at the edges of a unit structure
$G^A_{C,\text{FEM}}$	macroscopic fracture toughness obtained by FE analysis

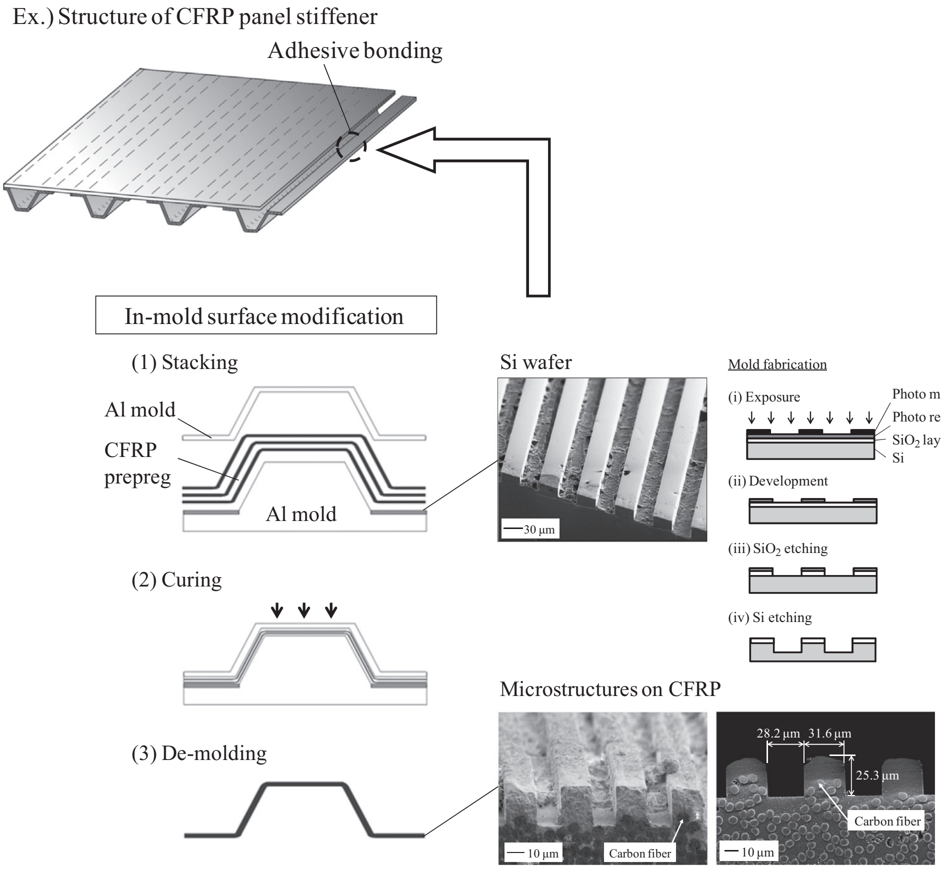

Fig. 1. A schematic of in-mold surface modification.

also difficult. Moreover, a large surface of uniform roughness can hardly be achieved by manual sand blasting. The foregoing, together with the critical factor of productivity in the application of composite materials in the automobile industry, has led to the urgent quest for more efficient surface modification methods.

To solve these problems, we previously proposed an in-mold surface modification method [11–15] that can be applied during the production of composite structures. In this method, microstructures fabricated on the forming mold are pressed against a low-viscosity matrix during curing, and the patterns are transferred by demolding at low temperature. By the periodic introduction of surface microstructures using this method, not only improved surface properties can be achieved, but the properties can also be controlled and optimized. This in-mold surface modification process is faster and cheaper compared to the conventional methods such as sand blasting, plasma etching, and milling.

In our previous work, we experimentally demonstrated the effect of microstructures on the tensile strength of butt joints [11], the macroscopic Mode I fracture toughness of a double cantilever beam (DCB) specimen [12], the macroscopic Mode II fracture toughness of an end notched flexure (ENF) test specimen [13]. We also investigated the effect of microstructures on the macroscopic mixed-mode fracture toughness of a single leg bend (SLB) test specimen [14]. Furthermore, we have previously investigated the quantitative relationship between the size and shape of the microstructures and the macroscopic Mode I fracture toughness based on the results of FE analyses [15]. The study revealed that a decrease in the macroscopic fracture toughness was accompanied by a decrease in size of the microstructures. Conversely, an increase in the aspect ratio resulted in an increase in the macroscopic fracture toughness. The increase in the aspect ratio also engendered transition of the fracture mode from interfacial fracture to cohesive fracture. In Ref [15], a simplified formula for predicting the macroscopic fracture toughness was developed based on the average energy consumption during crack growth; however, the difference between the predictions and those obtained by FE analysis became significant with increasing aspect