# The effect of surface morphology on Model-I fracture toughness of carbon fiber reinforced titanium laminates

**Z M Zheng, L Pan[1], L X Duan, Y Z Shen, Y B Hu, A Aamir, S Bhuwan and J Tao**

College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

E-mail: bettypan@nuaa.edu.cn

**Abstract**. The present study is focused on the relation between the microscopic sinusoidal surface morphology and model-Ⅰ fracture toughness of carbon reinforced titanium laminates, based on cohesive elements. The interface toughness was computed as a function of geometric parameters of the interface texture. The results suggest that the toughness is increased when wavelength (λ) increase, which provides the need to design fracture/failure resistance materials by carefully selecting the suitable parameters of the interface texture.

## 1. Introduction

Fiber-metal laminates (FMLs) are commonly used in engineering field due to their interesting mechanical properties. However, for relatively weak interfaces, stiffness and strength of composite were significantly decreased after low velocity impacts. The damage may not be visible with optical observation, retaining detrimental consequences, unless proactive action is taken.

As a dissimilar material, the interfacial failure is an important issue in designing, manufacturing and applications of laminates. A common effective method is to modify the interface by sand-blasting, etching or laser ablation [1-4], which introduces a certain microstructure and increase fracture/failure resistance. However, the quantitative relation between dissimilar materials has not been reported since random textures were created by those methods. Additionally, the scientists, find that various creatures also make full use of the interface texture from their shell, bond to plant stem [5-10] in its body in order to natural environment. In fact, the texture, such as the sinusoidal found in pearls and shell, tend to decrease the interfacial energy, which proves an increase in fracture toughness [11-12]. Also, there are many methods, such as lithography, to control this micro-pattern on the metal-polymer surface. In addition, delamination based on numerical simulation developed for 30-years. The method named the cohesive zone model (CZM) is considered as the most effective one. A number of studies have been focused on simulating of initial crack and extension with cohesive interface elements. C. Balzani and W. Wagner [13], studying a computerized simulation, utilize a cohesive model included both exponential model and linear softening model and, the results suggest that the exponential model is especial fit for FMLs delamination numerical simulation due to the improved convergence behavior.

In the present study, the effect of geometrical parameters on a sinusoidal interface was investigated, between metal (Commercially Pure titanium, Ti) and carbon fiber reinforced PEEK composite (CF/PEEK), through Finite Element (FE) simulations.

## 2. Materials and methods

The grade TA2 at thickness of 2 mm was considered as mental-base and the CF/PEEK composite was used as the reinforcing material.

To study the pattern effect of interface toughness between metal and polymer, a kind of commercial photoresist (SUN-1150P from SUNTIFIC, CHINA) was covered on the polished Ti surfaces, and then exposed to Ultra Violet through a patterned mask. The part of photoresist film which was exposed to Ultra Violet was developed to have a number of line patterns, whose width include 100, 200 and 300 μm using different masks. After exposing, in order to make micro-patterns on the Ti surface (figure 1), the part of the un-covered Ti surfaces of the Ti, developing solution was chemically etched in a mixed solution nitric acid and hydrofluoric acid. After that, 10 piles of pregreg stacked on the Ti surface and put onto a hot press in a certain pressure and temperature together. The ASTM D5528-01 standard [14], which has been well established for double cantilever beam (DCB), gives the preparation and characterizations details of DCB test.
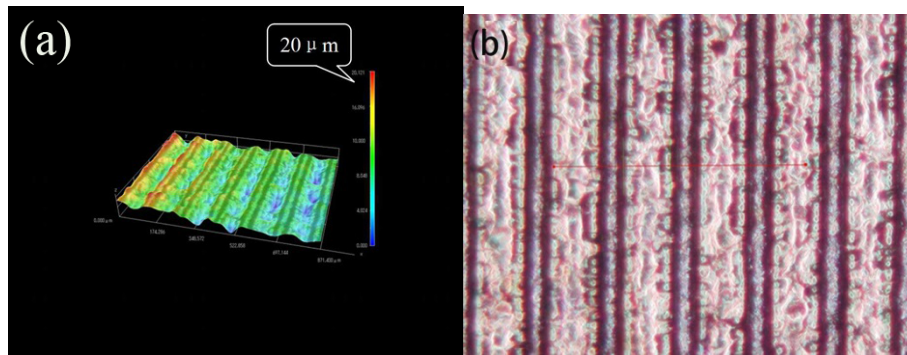


**Figure 1.** (a) 3D profile of the Ti interface after etching; (b) the surface coating with the photoresist.

## 3. Numerical modeling

A bi-linear cohesive zone law considered as the constitutive model of the cohesive elements describing the relationship between traction ($\sigma$) and displacement jump ($\delta$) at the interface where crack develops, which has a fundamental assumption that the initiation and evolution of interfacial failure experiences an initially linearly elastic behavior is employed in the present work.

Two TA2 panels and a CF/PEEK are bonded a along sinusoidal interface. For the sinusoidal interface, variables, such as the material properties, the applied load and geometric parameters, have significant effect on the critical interface toughness ($G_{IC}$). However, for the TA2/CF/PEEK laminate, the geometrical parameters which describe the characteristic of the sinusoidal patterns on the interface of Ti determine $G_{IC}$ as the others are constant. The sinusoidal interface is described by

$y(x) = A\sin\left(\dfrac{2\pi x}{\lambda}\right)$. Here, the initial crack tip position defined by Cartesian coordinate system (x, y =

0). For x < 0, the interface suffers an artificial crack, while for x ≥ 0, the interface is bonded and cohesive elements are inserted along sinusoidal interface while are used for simulating the interfacial delamination. In the case that the initial shape of the crack is defined by a straight line, having the initial artificial crack placed in the transition zone between a smooth and a sinusoidal part regarded this case is handled as the sinusoidal interface.

The specimens experience large deformation where geometrically and material non-linear finite elemental analysis should be considered. Otherwise, the materials experience both elastic deformation and plastic deformation. A von Misses isotropic plasticity model is used to control yielding.

Finite element software was employed for all simulations all simulation. The four-node is oparametric quadrilateral plane element, Plane182, was employed for solid materials. The relatively weak sinusoidal interface between Ti and CF/PEEK was represented by incorporating cohesive elements which are controlled by the bilinear softening model. These elements which carry the normal

and shear separation force between two solids describe weak interface. The contact pair incorporated with cohesive elements was inserted along the sinusoidal.

## 4. Results and discussion

The way of crack development by gradual stable growth, showed in figure 2(a), has three stages generally. In the first stage, the crack maintains its original position while stress concentration occurs. In the second stage, the stable crack occurs along the sinusoidal interface. In the third stage, the crack propagates rapidly when the load increases. At the same time, a typical cure describing the relationship both loading and displacement which is from DCB test, showed in figure 2(b), suggests that the interface failure mechanism is a slow transition from linear-elastic to elastic-plastic behavior as the loading going on when the crack development from the stable stage to unstable stage.
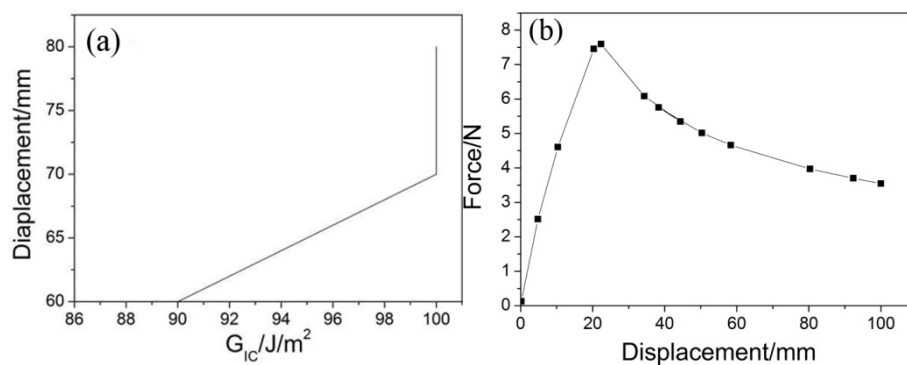


**Figure 2.** (a) Evolution of the crack propagation along the sinusoidal interface, showing increasing $G_{IC}$; (b) a typical cure describe the relationship both loading and displacement from DCB test.
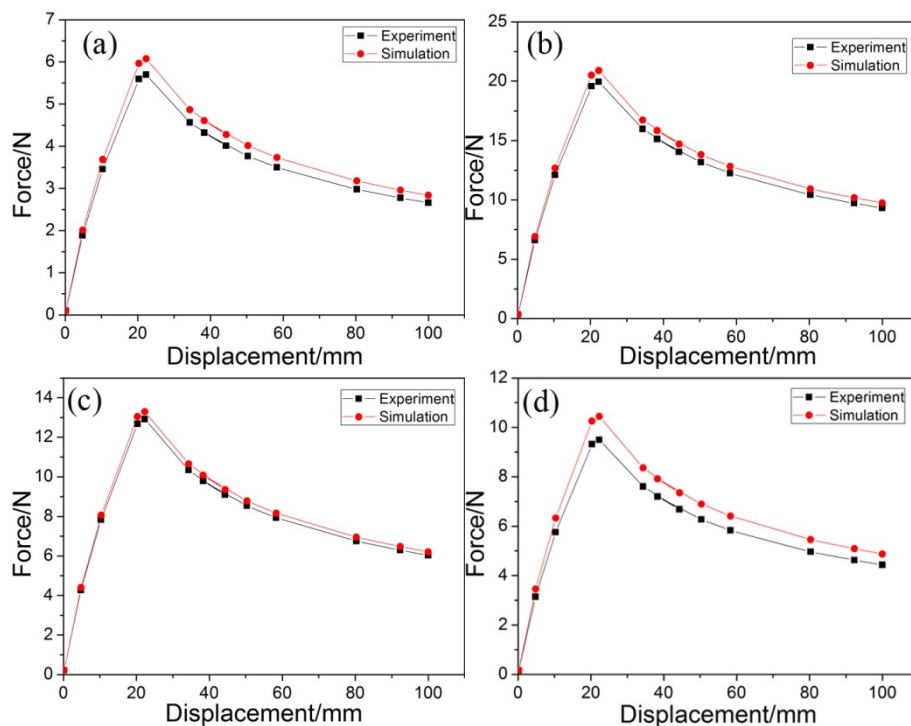


**Figure 3.** The results obtained from both experiment and numerical simulation of DCB of the specimens with sinusoidal interface: (a) $\lambda$ =0 μm, (b) $\lambda$=100 μm, (c) $\lambda$ =200 μm and (d) $\lambda$ =300 μm.

The typical cure describing the relationship both loading and displacement, indicate that the critical load is increased when the λ is increased and are in a good agreement with the calculated curves, as presented in figure 3. Both results of the simulation and DCB test demonstrate that the sinusoidal interface plays an important role in the critical loading, which increases when the value of the λ is increased.

The highest toughness value(G) was obtained for a wavelength of 200μm, while the G values that were obtained for 100 μm or 300 μm, were above the one obtained for a smoother interface. In order to study the reasons of failure, the interfaces were inspected by optical microscope. As seen in figure 4(a), there is not residual adhesive, adjacent the excavated region. However, the preserved region on the surface of titanium has many residual adhesive, as showed in figure 4(b). For the wavelength of 200μm, there is not only residual adhesive but also the carbon fiber was failed, as presented in figure 4c. The experiments demonstrate that the interface toughness can be manipulated by sinusoidal interface, which change the mechanism of crack propagation from adhesive failure to cohesive failure.
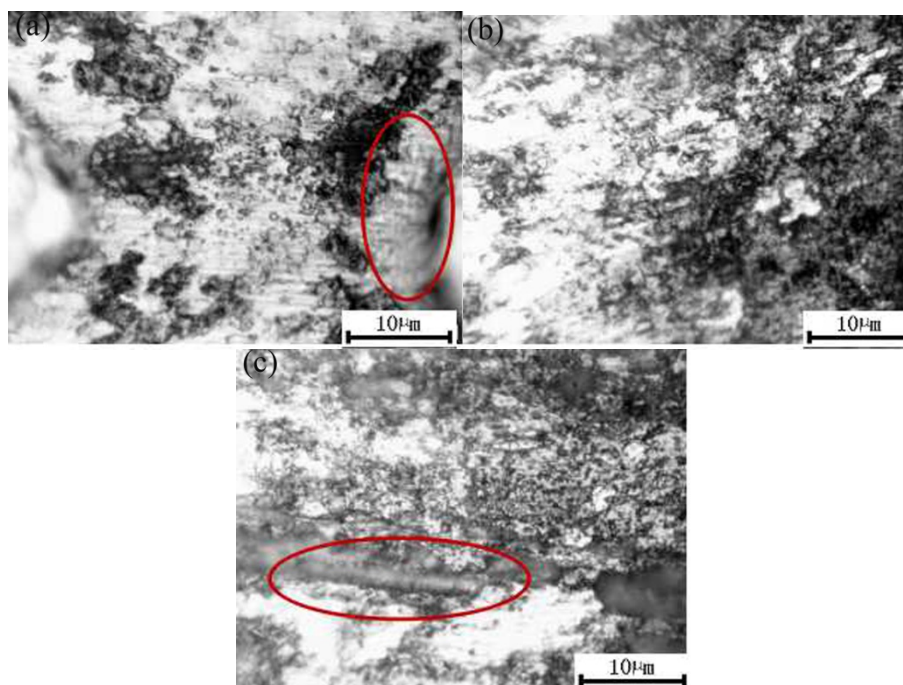


**Figure 4.** Surface of Ti at (a) wavelength with 300μm; (b) wavelength with 200μm.

Figure 5 shows the evolution of the stress distribution with the λ. For λ=100 μm, although many stress concentration fields were observed, the stress concentration field is relatively small, while the stress concentration field, adjacent to the peak of the sinusoidal interface, is relatively narrow, as can be observed in figure 5(b). The stress concentration field distribution presents a continuous morphology for λ = 0 μm and λ = 300 μm, as shown in figure 5(a) and 5(d), respectively. However, for a wavelength of 200 μm, the stress concentration field distribution demonstrated approximately seven discrete discontinuous peeks, while the total volume area is higher, compared to the area presented for a wavelength of 100 μm. Also, the stress distribution can affect polymer deformation near the interface, as showed in figure 4. The stress concentration field distributions indicate that the interface, in which a wavelength of 200 μm was employed, demonstrates a higher efficiency in energy dispersion when the crack propagation takes place along the sinusoidal interface.
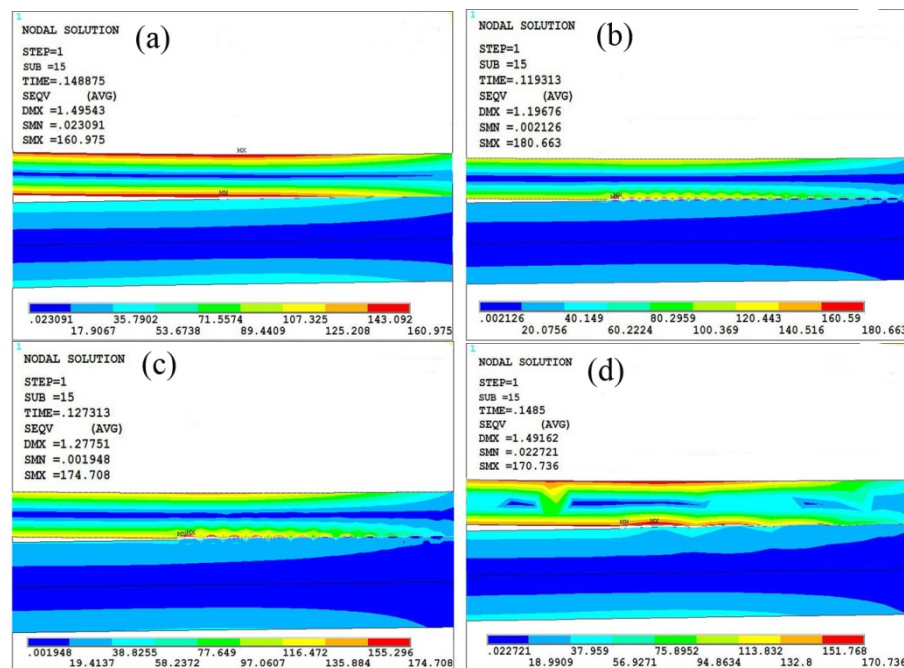
**Figure 5.** The stress distribution along with the interface for (a) λ=0μm, (b) λ=100 μm, (c) λ=200 μm and (d) λ=300μm.

## 5. Conclusions

The objective of the current work was to analyze the relationship between the interface toughness and the non-planar geometry characteristics. A sinusoidal interface was inserted between Ti and CF/PEEK. The major findings of the present study include that the interface toughness can be changed by selecting of the wavelength and amplitude, which supply suggestions for designing and manufacturing high interfacial fracture toughness FMLs.

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