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DESIGN AND FABRICATION OF THE GRADIENT FIBER COATING FOR METAL MATRIX COMPOSITES*

Hualun Li, Xiaohuong Liang, Zhiying Mao and Baolu Shang
Dept. of Materials Science and Engineering
Northwestern Polytechnical University, Xian 710072, China

Abstract

In this paper a new kind of carbon fiber coatings for metal matrix composites was designed and fabricated by chemical vapor deposition (CVD). The coating has a gradient structure in chemical composition. Its inside near the carbon fiber core is pyrocarbon and its outside is pure silicon. The intermediate sublayer between pyrocarbon and silicon is carbon and silicon carbide co–deposition, whose element concentration changs from 100% carbon to silicon carbide gradually. The gradient coating has functions in many ways, including wetting agent, diffusion and reaction barrier, release medium of residual thermal stresses, adjusting interface bonding strength, and mechanical fuses etc. Using the coated carbon fibers ($V_f = 0.35$), C / Al composites with longitudinal tensile strength up to 1250 MPa have been obtained by liquid infiltration method.

I. Introduction

In continuous fiber reinforced metal matrix composites, the interfacial zone controls many of the mechanical properties of the materials, including the axial and transverse strength and fracture resistance[1]. Various methods and ideas have been tried to get a interfacial zone which could meet requirements for the fabricating processes and the properties of the composites. Among them, fiber coating is a hopeful way to solve the problem, but the complex requirements make this task become diffeicult. In this paper a gradient fiber coating idea is presented to meet the challenge. The gradient fiber coating was performed by CVD. The coated fibers were used for obtainning C / Al composites.

II. Design of Gradient Coating

Fiber coating should be wetting agent, diffusion and reaction barrier, release medium of residual thermal stresses, adjusting interface bonding strength, and mechanical fuse for obtainning superior strength and toughness with simpler methods. Owing to the complex requirements, it is wery difficult to find a coating material for meeting the challenge.

A gradient coating is presented in this paper. Fig.1 shows a silicon carbide gradient coating on carbon fiber., The coating has a gradient structure in chemical composition. Its inside near carbon fiber surface is pyrocarbon. Its outside sublayer is pure silicon. The intermediate sublayer is carbon and silicon carbide co–deposition layer, whose element composition changs from 100% C to stoichiometrical silicon carbide gradually. The different sublayer of this gradient coating is entrusted different functions.

Wettable fibers could be dispersed in matrix uniformly with simpler ways. Various substances have been studied as wetting mediums. Sillicon is one of quasi–metals and it is able to be wetted easily by metals. It is one of the alloying elements in common aluminium alloys and it is of anti–oxidation at high temperature. The latter is important for preheating coated fibers in the fabrication processes of a composite. The remains of the silicon sublayer should be as thin as possible because it is harmful to the properties of composites. The layer will be solved in the forming processes of composites at low rate, especialy in liquid phase methods. For fibers to be uniform distribution in matrices, it is necessary that the silicon sublayer should not be exhausted before the solidification of melten matrices. It was experimentally found that after processing of liquid phase infiltration a silicon trace remains at the outside if the silicon sublayer has a thickness of $0.1\mu m$.

Silicon carbide is one of stationary materials to heat and chemistry, therefore, it was selected as the basic material of the gradient coating. The coefficient of temperature expansion (CTE) of silicon carbide is very different from that of carbon fiber. This big mismatch of CTE (4.6×10^{-6} and -0.35×10^{-6} respectely) will cause residual

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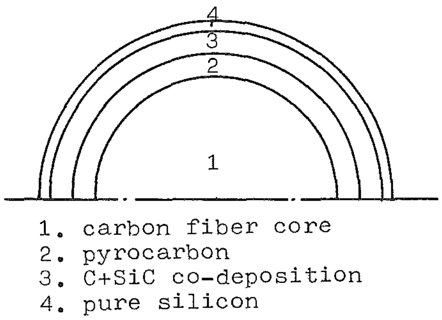


Figure 1. Scheme of SiC Gradient coating on Carbon Fiber

thermal stresses in the interfacial zone during the cooling–down peroid after deposition of the coating and processing of composite fabrication. The concentration of these permanent or transient stresses leads to a reduction of the interface properites. The common methods for reducting the stresses includ matching the properties of bonded bimaterials, forming intermediate layers, reducing coating thickness etc. For matching the difference by forming intermediate layers in silicon carbide and carbon fiber, six or more intermediate layers will be needful. In this state the residual thermal stress will not deteriorate the properties in interface zone, since the difference of CTE is less than 15% between two combined intermediate layers[2]. It is difficult to obtain so many intermediate layers. A gradient coating is equal to innumerless intermediate layers in behaviour, but gradient coating is much convenient for fabrication.

CVD silicon carbide is a brittle material. When the thickness of this brittle coating is below a critical value, C_I, the intrinsic defects of the fiber are more critical than those produced by the failure of the brittle layer, and composite will have high properties. The critical thickness can be calculated out form following formula[3]:

$$C_I\left\{F\left(\frac{a}{a+C_I}\right)\right\}^2 = \frac{G_c^*}{\pi\varepsilon_f^2 \cdot E_f} \qquad (1)$$

Where a is fiber diameter, G_c^* is critical strain energy release rate for the fiber. E_f is fiber elastic modulus, ε_f is fiber strain and $F(a/a+C_I))$ is geometry term related to relative thickness of fiber and brittle layer.

Calculating and considering gradient composition structure, the vale of $C_I$is 0.2 μm for PANⅡ carbon fiber.

There have been many theoretical and experimental studies of fracture in fiber composites. Summaries of failure mechanisms can be found in many references including Refs [4–6]. Experience has shown that when a crack moves through a matrix containing unidirectional fibers, the following failure mechanisms may be expected to operate: (1) matrix fracture at someplace. (2) fiber–matrix interface debonding, (3) post–debonding friction, (4) fiber failure, (5) stress redistribuiotn, (6) fiber pull–out, etc. It is belives that the failure of a composite is the processes of crack developing. In most reported cases, the formed reaction layer or defects in the matrix will fail at a small strain and form a circumferential notch. If the mothes extend into reinforcing fibers easly or immediately, the composite will fracture at low stress. On the other hand, if the crack tip develps along the interface of fibers easly and immediately, the transversal strength will be too low. Therefore, the central proplem of metal matrix composites leys to control the strength and toughness of the interface region. The interface region should act as mechanical fuses to arrest the impinging cracks, and contain the damage.

Many researches have analyzed the elastic stresses at the tip of a crack impinging at right angles to a bonded bimaterial interface having isotropic components[7]. Research results shown that the crack tip stresses are very sensitive to the modulus ratio. The tensile stress parallel to the interface in the cracked component increases rapidly as the cracked phase become realatively stiffer. This may cause fracture at low stress in this phase. On the other hand, as the modulus of the cracked phase becomes softer, the interface tensile splitting is the most likely failure mode.

Composites reinforced with SiC coated carbon fibers belong to the first case. If the inteface between fiber and SiC coating bond perfectly, the reinforcing fibers in this cmposites could fracture at low stress. This can be rectified by coating a soft pyrocarbon on the carbon fiber suface. The soft intermediate layer can change the direction of crack from its main direction to the interface to avert low stress fracture of fibers.

The soft intermediate layer is benificial to the longitudinal strength of composites but it is unfavourable to the transverse strength if the interfacial shear strength is too low. Therefore it is neccessary to tailor the interfacial shear or bonding strength.

According to the resaerch of Ochiai[8], when the failure strength of bare fiber, σ_f , and the notch forming strength of a coated fiber σ_f^0 , and the notch extending strength σ_f^* , and debonding trength $\sigma_f^{\triangle}$ correspond to the following sequence:

$$\sigma_f > \sigma_f^* > \sigma_f^{\triangle} > \sigma_f^0 \qquad (2)$$

the composite will have high longitudinal and better transverse strength. In order to obtain higher transvese properties, $\sigma_f^{\triangle}$ should be enough high under keeping the sequence above. The value of $\sigma_f^{\triangle}$ is influenced by many factors[9]:

$$\sigma_f^{\triangle} = \tau^{\triangle} E_f \{2\pi a\,(G_b \bar{r}_f + G_f \bar{r}_b) \cdot (1/A_b E_b + 1/A_f E_f)/G_b G_f\}^{\frac{1}{2}} \qquad (3)$$

where $\tau^{\triangle}$ is the intefacial shear strength, G is shear modulus, A is the cross–secional area, a is the diameter of the bar fiber, b is the diameter of coated fiber. and r_b , r_f , A_b are given by $\bar{r}_b = \{a^2 + b^2)/2\}^{\frac{1}{2}} - a$, $\bar{r}_f = 0.39a$, $A_b = \pi(b^2 - a^2)$, $A_f = \pi a^2$.

Therefore, the $\sigma_f^{\triangle}$ can be adjusted by changing the thickness of pyrocarbon intermediate, different system has its sutable value, which can be obatined by calculation or experiments. A pyrocarbon layer of 0.2μm in thickness was adopted in this research.

Ⅲ. Experimental

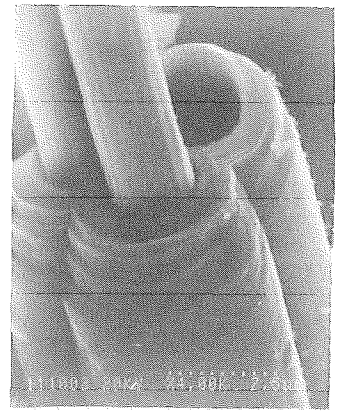
The carbon fiber gradient coating was performed by chemical vapour deposition. The composition chang was performed with the chang of temperature field or the chemical composition filed of vapour phase. The composition profile across coating was obtained by Auger electron spectroscopy (AES) / argon ion sputting perpendicular to the coated fiber surface. Carbon fiber was PANⅡ yarn fiber and each yarn has 1000 filaments of 7–8μm diameter.

The morpholgy of the coated fiber was characterized by scanning electron microscopy (SEM).

The coated fibers were used for fabrication of C / Al composites by vacuum–pressure infiltration processing. The matrix was Al–7Si–0.3Mg alloy. The size of tensile sample is 6mm in diameter and 100mm in length. The cast state tensile strength was tested with Instron 1196 tensile machine at a loading rate of 0.5mm / sec.

Ⅳ. Results

The thermodynamics and kinetics of CVD of Si, SiC and C, and the parameters of CVD processsing have been extensively researched. The deposition temperature and vapour compostion in processing are the most parameters. The principle for selecting paraeters is to obtain quality depostion layer at high rate. Fig.2 shows the morphology features of the functionally gradient coating. The structure of sublayers in the coating can been seen perfectly. At the same time we can see the some bonding features at the interface. Fig.3 is the chemical composition distribution along the direction of coated fiber radius. In this figure, it can been found that the gradient chemical chang from the inside to the outside and the sublayer thicknesses are in keeping with the design of the gradient fiber coating. C / Al composites reinforced with the coated fibers were fabricated by vacuum pressure lqiuid infiltrition. The distribution of fibers was uniform and wetting state was perfect. A longitudinal tensile strength of 1250 MPa was obtained in the C / Al composite reinforeced with the coated fibers (V_f = 0.35).



Figuer 2. Morphology of the Gradient Coating with Fiber Core.

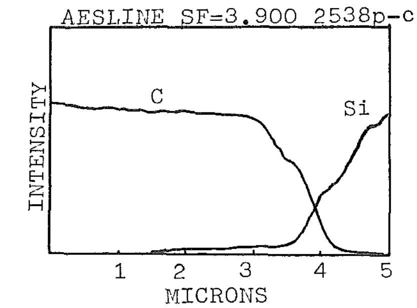


Figure 3. AES Radial Element Distribution Profile of the Coated Fiber

Ⅴ. Conclusion

1. The gradient fiber coating is a new fiber coating

for metal matrix composites. The gradient coating possesses a few functions which could meet many requirments of metal matrix composites.

2. The design of interfacial zone of metal matrix composites could be achieved by gradient fiber coating which possesses designability.

3. The gradient coating on carbon fibers can performed by chemical vapour deposition.

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