METALS AND MATERIALS, Vol. 4, No. 3 (1998), pp. 242~246

A Pseudo-Plastic Engagement Effect on the Toughening of Discontinuous Fiber-reinforced Brittle Composites

Xiao-Yu Liu, Wei-Dong Yan and Nai-Gang Liang

LNM, Institute of Mechanics, Chinese Academy of Sciences
Beijing 100080, P.R. China

In brittle composites, such as whisker reinforced ceramics, the sliding of reinforcing fibers against the frictional resistance of matrix is of a pseudo-plastic deformation mechanism. High aspect-ratio whiskers possess larger pseudo-plastic deformation ability but are usually sparse; while, low aspect-ratio ones were distributed widely in the matrix and show low pseudo-plastic deformation ability (engagement effect), also. A comparative investigation was carried out in present study based on a multi-scale network model. The results indicate that the effect of low aspect-ratio whiskers is of most importance. Improving the engagement coefficient by raising the compactness of material seems a more practical way for optimization of discontinuous fiber-reinforced brittle composites in the present technological condition.

Key words : engagement effect, bridging, discontinuous fiber-reinforced brittle composites, multi-scale network model, strengthening/toughening of material

1. INTRODUCTION

Discontinuous fiber-reinforced brittle composites, such as *in-situ* and *SiC*-whisker reinforced ceramics, received considerable attentions in the past three decades due to their commercial importance [1]. One of the principal assumed toughening mechanisms is crack bridging [2]. The crack bridging theory postulates that intact whiskers or elongated grains behind the primary crakc front bridge the crack surfaces in the following wake region, thus inhibiting farther crack opening and reducing the stress intensity at crack tin [3]. As a result, the whiskers are partially or completely pulled out from the matrix along the crack plane.

An approach to understand the bridging effect is to analyze the relationship between average crack opening displacement u and the whisker-matrix interfacial shear stress τ. A typical relationship is shown in Fig. 1(a) (reprinted from Fig. 13, Chien-Wei Li *et al.*, J. Am. Ceram. Soc. 78(2) 449-59, 1995). The rise of τ when u is small can be attributed to an increase in elastic strain in the bridging elements, and the falloff of τ when u becomes large can be attributed to the pullout of bridging elements.

For those high aspect ratio whiskers (i.e., length/diameter > 4), the limitation of elastic deformation is generally 10^{-3} of the whole fiber length. Supposing the total pullout length is 10^{-2} or 2×10^{-2} that of the whisker, the $\tau(u)$ relationship can be further specified by a parameter ω, which denotes the proportionality of the maximum of plastic strain and that of the elastic strain. Generally, ω varies from 10 to 20 for the material considered, which shows a strong pseudo-plastic behavior or pseudo-plasticity. In this viewpoint, the fiber-reinforced composites can be described by a multi-scale network model [4, 5] that consists of a pure matrix embedded with distributed chains that possess certain ideal plastic deformation mechanism as given in Fig. 1(b), in which $\omega = \frac{AB}{OC}$.

Numerical investigation shown in Fig. 2 indicated that the pseudo-plastic bridging of high aspect ratio whiskers does not seem to take its full effect because the primary cracks always avoid those long whiskers when they propagate.

Again, as shown in Fig. 3, the stress-strain curves, arranged in three rows and three columns according to the values of ν and L_f-R_f (see Table 1), respectively, indicate that the maximum of strength does not obviously increase unless the volume fraction of high aspect ratio whiskers reaches a certain threshold. This threshold, however, is rather difficult to reach as far as present technological conditions are considered. Therefore, it seems that high aspect ratio whiskers can not play a great role in toughening ceramics.

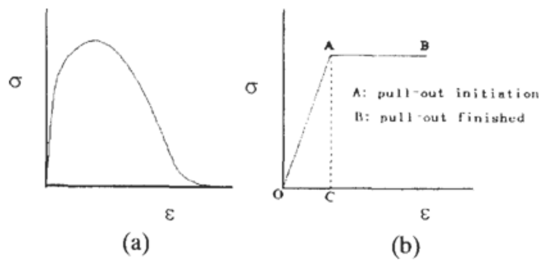

Fig. 1. (a) Schematic of a typical $\tau(u)$ relation for bridging (taken from Jeffrey Goldacker *et al.* [7]). (b) The stress-strain behavior of an ideal elastic-plastic chain considered in present model.

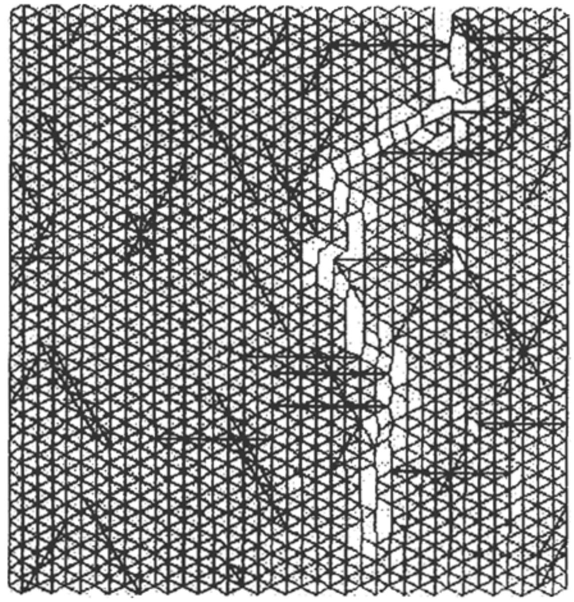

Fig. 2. The damage evolution of short fiber reinforced composites.

For those low aspect ratio whiskers, whose aspect ratio is less than 4, experimental results point out that their volume fraction is much higher than that of high aspect ratio whiskers and, that they are widely distributed [6]. As shown in Fig. 4 (in which the specimen was supplied by Shanghai Institute of Ceramics, Chinese Academy of Sciences), there are a lot of debonding and pullout of short whiskers in the area cracking. The low aspect ratio whiskers also possess the pullout mechanism [7]. As was pointed out by Jeffrey Goldacker *et al.*, the medium-size grains may also effectively bridge the cracks, and their contribution to toughening can be significant be-

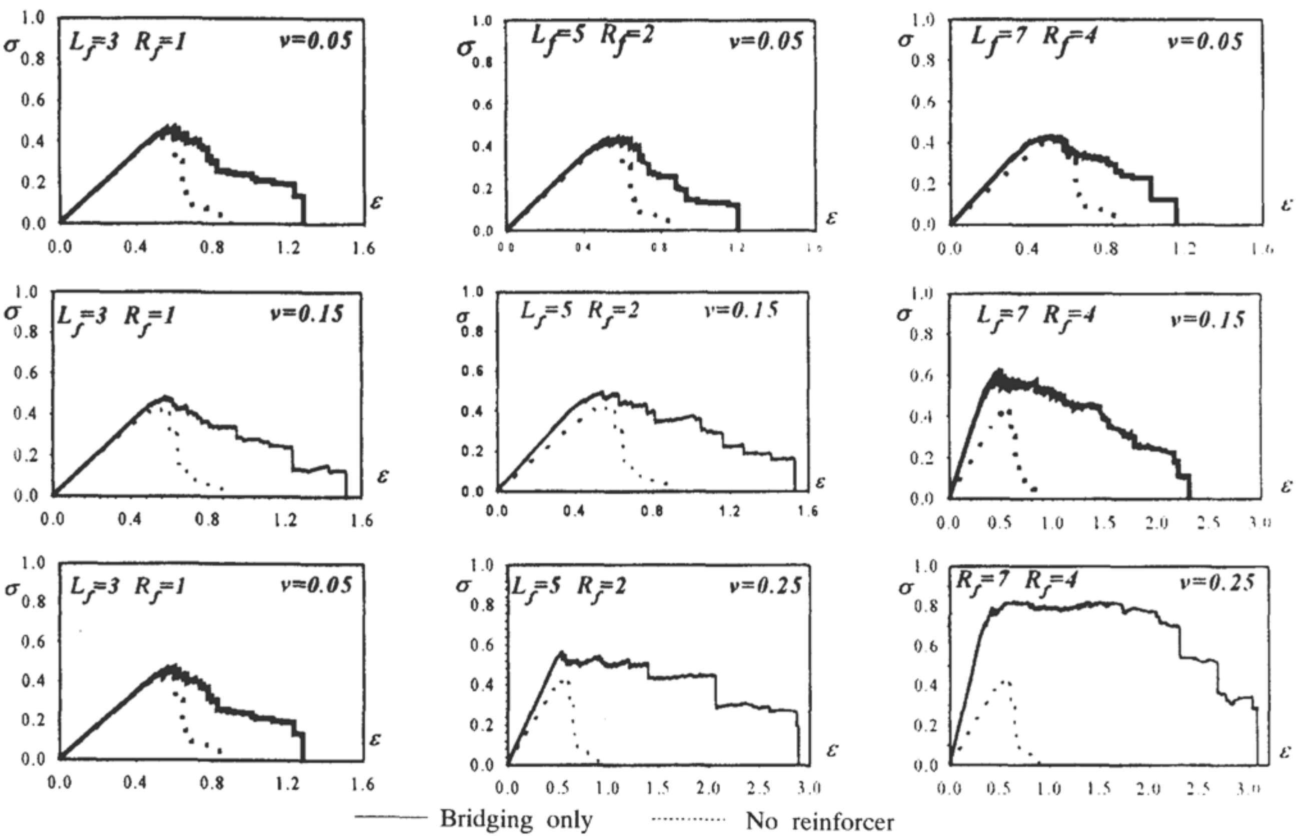

Fig. 3. The stress-strain curves to show bridging effect of high aspect ratio reinforcers.

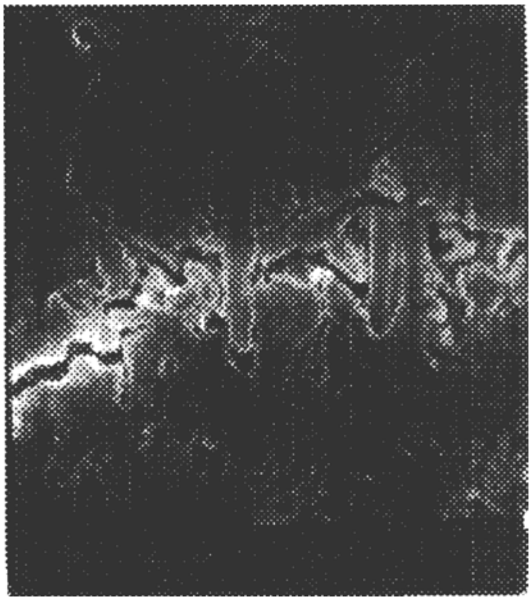

Fig. 4. SEM photo indicating the engagement of low aspect ratio reinforcers.

cause of their large populations. For this reason, in this paper, the contribution of low aspect ratio whiskers is specially named as an engagement effect to be distinguished from bridging effect.

However, until now few quantitative analyses were reported on engagement effect. Therefore, on the basis of our previous work on studying high aspect ratio whiskers [4,5], this paper focuses on the engagement effect. The influence of low aspect ratio whiskers on the material properties is investigated, and parameter optimization schemes are discussed.

2. A COMPUTATIONAL MODEL

A multi-scale network model is proposed with a subdivision of triangle-elements, to simulate the uniaxial tensile specimens having two ends fixed on rigid carriage [4, 5]. In present study, all the discussion is limited to a plane stress problem. Table 1 is a list of the material parameters involved in the model.

As usual, the high aspect ratio whisker is treated as a large chain that consists of several small chains according to its aspect ratio L_f. Their position, orientation, length and rigidity are all arranged statistically. When the tensile stress exerted on the large chain reaches its maximum at which the interface debonding occurs, the chain slides along the interface then to break or load-off.

Similar to the treatment of high aspect ratio whisker, the overall stress-strain response of pullout of low aspect ratio whiskers is also supposed to consist of an elastic stage and a plastic stage. The engagement coefficient of low aspect ratio whiskers, ω, is assumed to vary from 2 to 8 in present calculation.

Table 1. A list of parameters used in present material model

Meaning	Symbol	Typical values (A.V.)
Rigidity modules of matrix	r_m	1, as rigidity scale
Fracture strain of matrix	b_m	1, as strain scale
Length of matrix chain	1	1, as length scale
Initial damage fraction	d_m	0, initially not
Effective width of reinforcer	W	$\frac{2}{3}l$
Aspect ratio of reinforcer (l/w)	L_f	4, 6, 8
Rigidity modules of reinforcer	R_f	1, 2, 4
Volume fraction of reinforcer	V	$(5.0\times n)\%$, n=1~5
Reinforcer-stress/$(b_m\times s_m)$ at interface debonding	S_i	0.25×2^n, n=0~4
Eq-strain of reinforcer pullout	B_f	2~5%
Overall strain/b_m	ε	
Overall stress/$(b_m\times r_m)$	σ	

As far as the large population and wide distribution of low aspect ratio whiskers are considered, the whiskers and matrix grains can be converted together into small chains in the multi-scale network model for simplicity. According to the heterogeneity of material, Young's modules and the fracture strain of small chains are varied randomly. Their fluctuation is expected to be able to describe the statistical character of material.

3. CALCULATED RESULTS

For different combination of parameters, the overall stress-strain curve is examined. Comparison of these pictures will give an insight into the effect of the combinations of engagement and the other parameters on the overall mechanical properties of the composites.

The simulated results display a random behavior because of the intended heterogeneity of microstructure and physical property of the material. In order to find out the statistical relationship between the parameters used and the macro properties of material, seven stress-strain curves are calculated for each of the parameter combinations and the medial curve is selected for comparison.

Fig. 5 shows five macro stress-strain responses with engagement effect rather than the bridging effect considered. Each curve corresponds to parameters of ω=0.5,

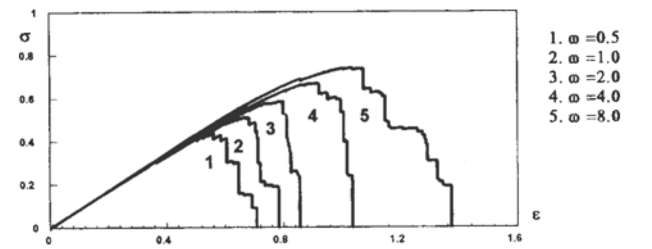

Fig. 5. The stress-strain curves of short fiber reinforced composites to show engagement effect.

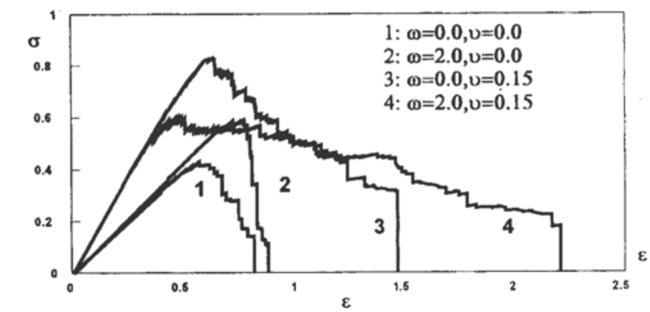

Fig. 6. Comparing of engagement effect and bridging effect on the stress-strain response of short fiber reinforced composites.

1.0, 2.0, 4.0, and 8.0, respectively. It can be seen from these figures that the maximum of stress response of material increases with the increment of the engagement coefficient; in other words, the engagement of low aspect ratio whiskers can improve the material properties.

Fig. 6 shows four stress-strain curves with respect to different engagement coefficients respectively, and meanwhile the volume fraction of high aspect ratio whiskers possessing certain pseudo-plasticity is also specified at different values respectively. The comparison between the curve of "ω=2 and ν=15%" and the curve of "ω=0 and ν=0%" reveals that if the material possesses some engagement ability and at the same time, the volume fraction of high aspect ratio whiskers is controlled at a moderate value, the strength of material can be remarkably improved.

The curves of "ω=0 and ν=15%" and the curve of "ω= 2 and ν=0%" point out that the macro stress response to engagement of low aspect ratio whiskers (ω=2) is almost equivalent to that of high aspect ratio whiskers whose volume fraction is as high as ν=15%. This supports the conclusion that the engagement effect acts as a great role in strengening material.

Fig. 7 shows 4 groups of stress-strain curves, arranged in 2 rows and 2 columns according to value of ν and L_f-R_f, respectively. Each group includes three curves corresponding to no whisker introduced, no engagement effect and engagement of magnitude ω=2, respectively. Some common features can be obtained by comparative analysis of the simulated stress-stain curves. Despite the maximum of the stress response increases with the increase of the volume fraction of high aspect ratio whiskers, the degree of improvement is not obvious until the volume fraction reaches a certain value. However, this is not the case if the engagement effect is considered. Furth-

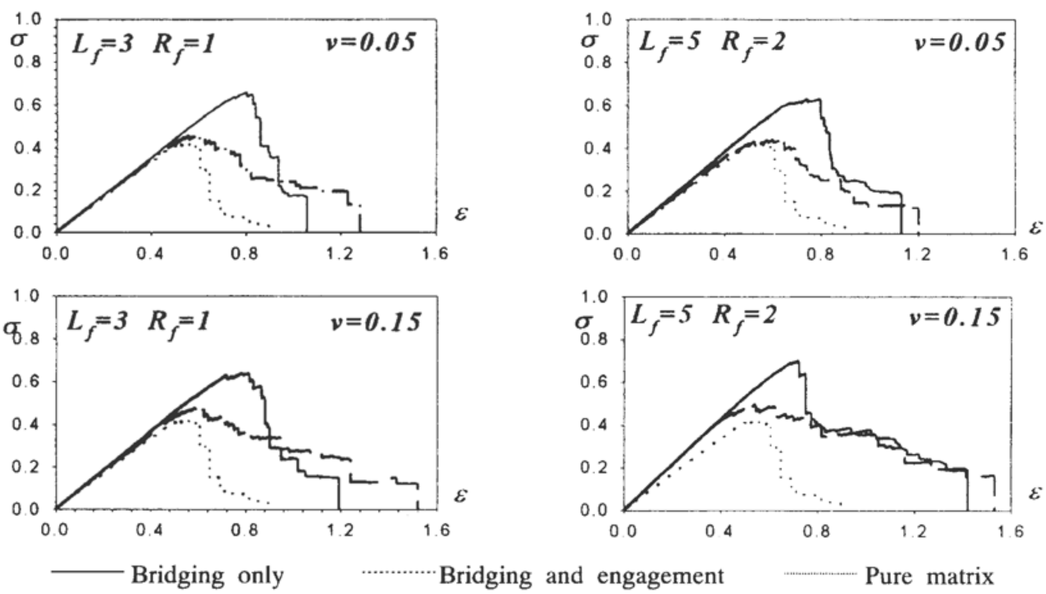

Fig. 7. The stress-strain curves for comparing bridging effect and engagement effect.

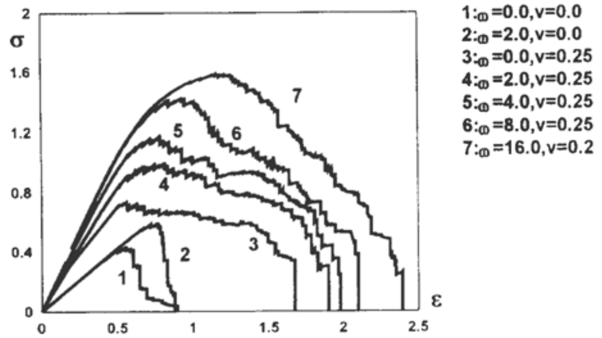

Fig. 8. The stress-strain curves go up with the increment of engagement effect and bridging effect.

ermore, it seems that the toughening mechanism of present material originally considered to be the bridging of high aspect ratio whiskers may be completed by engagement effect of low aspect ratio whiskers in many cases.

4. CONCLUSION AND DISCUSSION

The numerical investigation carried out in present paper points out that there are at least two ways to improve the toughness of discontinuous fiber-reinforced brittle composites. One is to raise the volume fraction of high aspect ratio whiskers, the other is to improve the engagement of low aspect ratio whiskers. As far as present technological condition is considered, the second way may possess more advantage because the high volume fraction of reinforcers usually causes low interface-bonding-strength and more heterogeneity. On the other hand, raising the compactness of material can improve the engagement. If the engagement reaches a certain value, e.g. 16, and if the volume fraction of high aspect ratio whiskers can be controlled as high as 25% without bringing out other side effects, an ideal result is obtained as shown in Fig. 8 (line#7), in which the strength of material is greatly improved.

Therefore, paying full attention to the effect of engagement and meanwhile, improving the volume fraction of high aspect ratio whiskers as high as possible, seems a good way to material toughening.

ACKNOWLEDGMENT

The work was supported by the National Natural Science Foundation of China. The authors thank the assistance of Shanghai Institute of Ceramics, Chinese Academy of Sciences.

REFERENCES

1. Mamoru Mitomo and G. Petzow, *MRS Bulletin* **Feb.**, 19 (1995).
2. Paul F. Becher, Shyh-Lung Hwang and Chun-Hway Hsueh, *MRS Bulletin* **Feb.**, 23 (1995).
3. Frank D. GAC., Ceram. *Eng. Sci. Proc.* **11**, 551 (1990).
4. N. Liang, Q. Liu, J. Li and H. Song, *Advance in Engineering Plasticity and Its Applications* (eds., T. Abe and T. Tsuta), 1st Ed., p. 141, Permamon, Tokyo (1996).
5. N. Liang, Q. Liu and H. Xu, "A Multi-Scale Network Model and Parameter Optimization of Discontinuous Fiber Reinforced Brittle Composite", *Proc. of IMMM97*, Japan (1997).
6. Pavol Sajgalik, J. Dusza and M. J. Hoffmann, *J. Am. Ceram. Soc.* **78**, 2619 (1995).
7. Chien-Wei Li, Siu-Ching Lui and Jeffrey Goldacker, *J. Am. Ceram. Soc.* **78**, 449 (1995).