

This article was downloaded by: [Renmin University of China]

On: 13 October 2013, At: 11:34

Publisher: Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Advanced Composite Materials

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/tacm20>

A study of the residual stress and its influence on tensile behaviors of fiber-reinforced SiC/Al composite

Yun Lu ^a, Liang Hao ^b, Fusheng Pan ^c, Jinxiang Chen ^d & Mitsuji Hirohashi ^a

^a Faculty of Engineering, Graduate School, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522, Japan

^b Graduate School, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522, Japan

^c College of Materials Science & Engineering, Chongqing University, No 174 Shazhengjie, Shapingba, Chongqing, 400044, China

^d International Institute for Urban Systems Engineering & School of Civil Engineering, Southeast University, Nanjing, 210096, China

Published online: 22 May 2013.

To cite this article: Yun Lu, Liang Hao, Fusheng Pan, Jinxiang Chen & Mitsuji Hirohashi (2013) A study of the residual stress and its influence on tensile behaviors of fiber-reinforced SiC/Al composite, *Advanced Composite Materials*, 22:4, 255-263, DOI: [10.1080/09243046.2013.802119](https://doi.org/10.1080/09243046.2013.802119)

To link to this article: <http://dx.doi.org/10.1080/09243046.2013.802119>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

A study of the residual stress and its influence on tensile behaviors of fiber-reinforced SiC/Al composite

Yun Lu^{a*}, Liang Hao^b, Fusheng Pan^c, Jinxiang Chen^d and Mitsuji Hirohashi^a

^aFaculty of Engineering, Graduate School, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan; ^bGraduate School, Chiba University, 1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan; ^cCollege of Materials Science & Engineering, Chongqing University, No 174 Shazhengjie, Shapingba, Chongqing 400044, China; ^dInternational Institute for Urban Systems Engineering & School of Civil Engineering, Southeast University, Nanjing 210096, China

(Received 4 May 2012; accepted 29 October 2012)

Unidirectional fiber-reinforced SiC/Al composite was fabricated by hot pressing. The residual stress in the composite generated by heated treatment, sub-zero treatment, or pre-loading was measured by X-ray diffraction. In addition, tensile tests were carried out for the composite, and the effect of the residual stress on the tensile behaviors was evaluated by both the experimental investigation and the calculation analysis based on the rule of mixture (ROM) taking the residual stress into account. The experimental results showed that the residual stress had great influence on the tensile stress when the tensile stress was small; while the influence became weaker and weaker with the increase in tensile stress and almost disappeared when the tensile stress reached the ultimate tensile strength. Furthermore, the residual stress almost had no effect on Young's modulus of the SiC/Al composite. The calculation analysis based on the ROM taking the residual stress into account was found to be a simple and effective way to evaluate the effect of residual stress on the tensile behaviors of the SiC/Al composite.

Keywords: fiber-reinforced composite; residual stress; tensile behavior; hot pressing; rule of mixture

1. Introduction

During the fabrication process, such as forming or heat treatment, of fiber-reinforced metal matrix composites (MMCs), residual stress is inevitably produced due to the different thermal expansion coefficients between the matrix and the reinforcements. It is well known that residual stress has a great influence on many properties of fiber-reinforced MMCs, such as mechanical property, fatigue property, and corrosion resistance, among others. Considerable works have been reported on the formation and analysis, [1,2] the models,[3] the measurement,[4,5] the computer simulation,[6,7] the interface [8,9] of the residual stress in fiber-reinforced MMCs. Though some studies about the effects of residual stress on the mechanical properties of fiber-reinforced composites including compressive strength,[10] yield strength,[11] tensile strength [12] of fiber-reinforced MMCs have been done, the work about the residual stress and its effect on the tensile behaviors of fiber-reinforced SiC/Al composite has been reported scarcely.

*Corresponding author. Email: luyun@faculty.chiba-u.jp

In the present study, fiber-reinforced SiC/Al composite was fabricated by hot pressing. Residual stress was produced by heat treatment, sub-zero treatment, and unidirectional pre-loading. Tensile tests were carried out to investigate the residual stress and its influence on the tensile behaviors. The residual stress was measured by grazing incidence X-ray diffraction (GIXD). Besides, the combination of experimental investigation and the calculation analysis based on the rule of mixture (ROM) taking the residual stress into account was applied to evaluate the residual stress.

2. Experimental and calculation analysis method

2.1. Fabrication and post-treatments of the SiC/Al composite

A1050 aluminum plate with a thickness of 0.2 mm was used as the matrix material of the SiC/Al composite. SiC_{CVD} fiber (produced by chemical vapor deposition), fabricated by Textron Specialty Materials (type SCS-2, diameter: 140 μm), was used as the reinforcement. The SiC/Al composite was fabricated by the following process. Firstly, the A1050 aluminum plate was cut into pieces of 30 mm \times 70 mm, which were then annealed at 573 K for 30 min in air. Secondly, U-shaped grooves with interspaces of 0.5 mm were made on one surface of the aluminum plate by pressing the stainless steel wires with a diameter of 140 μm into the Al plate. Thirdly, SiC_{CVD} fibers with a length of 70 mm were put into the grooves, and then, another SiC fiber was placed between the two fibers, which had existed in the grooves. After that, one sandwich layer SiC/Al preform was obtained by overlapping one pure Al plate with the same dimension on that Al plate arranged with the SiC fibers. Finally, three preforms were superimposed and processed by hot pressing in air. The temperature, pressure, and holding time of hot pressing were 893 K, 56 MPa, and 40 min, respectively.

Figure 1 shows the cross-section microstructures of the SiC/Al composite fabricated by the hot pressing. It can be seen that the SiC/Al composite has a microstructure of unidirectional three-layer SiC fiber, and the interlayer spacing of SiC fibers was about 0.25 mm (Figure 1(a)). However, the inter-fiber spacing is heterogeneous. The heterogeneous distribution will have effect on the tensile behavior. The effect will be discussed in the following section. The SiC fiber volume fraction (V_f) was about 9.2%. From Figure 1(b), there is no obvious gap between SiC fibers and Al matrix on their interface. It means that the SiC/Al composite should have a strong interface bonding.

To obtain the same initial residual stress condition and surface condition, the surface of the SiC/Al composite was polished by about 10 μm . Then, the specimens were heated at 823 K holding for 5 min. After that, different cooling rates were adopted to produce different residual stress conditions (shown in Table 1). In the case of pre-loading (sample VI), the specimen was loaded along the direction of SiC fibers. That gave the specimen a stress of 95.9 MPa which is about a quarter of the yield strength (383.4 MPa) of the SiC/Al composite. According to the pre-experiments, the matrix could yield but the SiC fibers would not damage under the above pre-loading.

2.2. Measurement of the residual stress and the tensile tests

The residual stress along the fiber direction and the right angle direction was measured by GIXD. The measurement conditions of X-ray diffraction are listed in Table 2. To remove the oxide film on the sample surface, the surface was polished uniformly before X-ray analysis. The residual stress, σ_r , was calculated using the Equations (1) and (2).

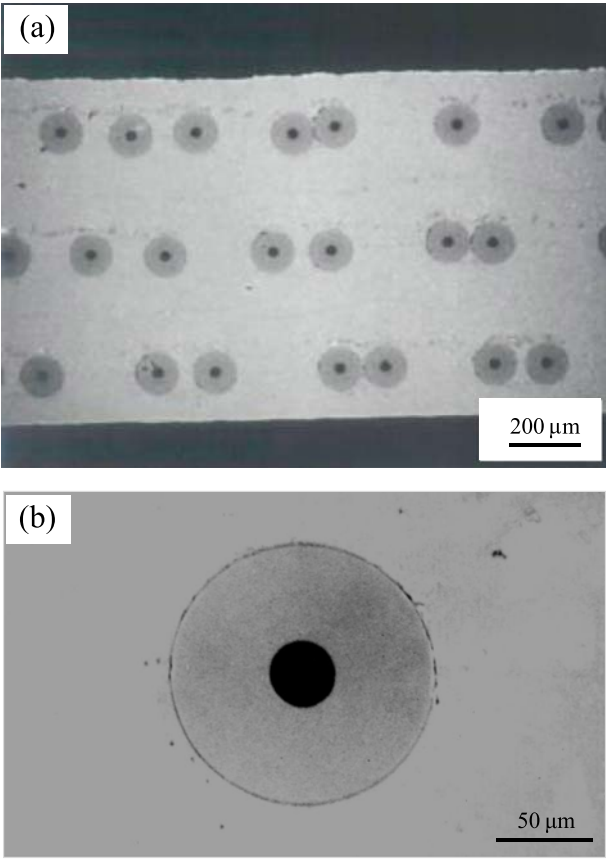


Figure 1. The cross-section microstructure of the SiC/Al composites.

Table 1. Post-treatments of the SiC/Al composites.

Sample number	Post-treatments
I	823 K × 5 min annealed
II	823 K × 5 min air cooling
III	823 K × 5 min water quenched
IV	77 K × 10 min sub-zero treated
V	176 K × 10 min sub-zero treated
VI	Pre-loading (95.9 MPa)

$$\sigma_r = -KM \tag{1}$$

$$K = E \cot \theta_0 / 2(1 + \nu) \tag{2}$$

where K is the stress factor, M is the slope of 2θ - $\sin^2\psi$ diagram, $M = \partial(2\theta)/\partial(\sin^2\psi)$, E is Young's modulus, and ν shows Poisson's ratio, while θ represents the diffraction angle of (422) plane of the Al matrix, and θ_0 represents the diffraction angle of (422) plane when the Al matrix has no residual stress. In the present investigation, the $2\theta_0$

Table 2. Measurement conditions of X-ray diffraction.

X-ray diffraction items	Measurement condition
Characteristic X-ray	Cu-K α
Tube voltage and current	40 kV, 35 mA
Measuring method	Para-focusing Ω -diffractometer
Irradiated area	20 mm \times 20 mm
Diffraction plane	Al (422)
Counting time (sec)	5.00
Angle interval (deg)	0.08
Ψ (deg)	0.00, -19.00, -23.00, -29.00, -34.00, -40.00, -43.00, -45.00

diffraction angle of (422) plane of pure Al plate, which was annealed at 823 K and holding for 30 min, can be substituted by 137.799°. Young's modulus E and Poisson's ratio ν were substituted by 69.5 GPa and 0.33, respectively.

Tensile tests were carried out at room temperature by a tensile testing machine (Shimadzu, AG-5000ES). The tensile specimens have a dimension of 70 mm \times 6 mm \times 1 mm. A constant tensile speed of 0.05 mm/min and a gauge length of 10 mm were adopted. A strain gauge was applied to the center along the tensile direction of each tensile specimen. To understand the strength of the SiC fiber in the SiC/Al composites, tensile tests of the SiC fibers, which were extracted by dissolving the matrix with 10%NaOH water solution, were also carried out. Besides, to obtain the parameters of mechanical properties of the Al matrix, tensile tests were performed for pure Al specimen with the same dimension as the SiC/Al composite specimen.

2.3. Calculation based on the ROM taking the residual stress into account

In the present study, the residual stress was introduced into ROM to evaluate the effect of the residual stress on the tensile behaviors during the tensile tests. Firstly, it was supposed that the residual stresses of both the matrix and fiber, σ_{mr} and σ_{fr} , follow ROM. It was presumed that the relationship between the stress and strain of the matrix follows n-power hardening rule. The residual strain of the matrix and fiber, ε_{mr} and ε_{fr} , can be calculated by ROM.

$$\sigma_{fr}V_f + \sigma_{mr}(1 - V_f) \quad (3)$$

and

$$E_f\varepsilon_{fr}V_f + \sigma_{mr}(1 - V_f) = 0 \quad (4)$$

Then, the fiber residual strain is

$$\varepsilon_{fr} = -\{\sigma_{mr}(1 - V_f)/E_fV_f\} \quad (5)$$

And the residual strain of the matrix is

$$\varepsilon_{mr} = \sigma_{mr}/E_m \quad (\sigma_{mr} < \sigma_y) \quad (6-1)$$

$$\varepsilon_{mr} = (\sigma_{mr}/K)^{1/n} \quad (\sigma_{mr} < \sigma_y) \quad (6-2)$$

Table 3. Parameters used in the ROM calculation.

σ_{my} (MPa)	E_m (GPa)	K (MPa)	n	E_f (GPa)	V_f (%)
23.2	69.5	192.3	0.262	421	9.2

Then, the residual stress of the composite during the tensile tests can be evaluated by substituting the residual strain of the matrix and fiber into the ROM as shown in Equations (7-1) and (7-2) and making the composite strain (ε_c) increase with a step of 0.001% till 1.0%.

$$\sigma_c = E_f V_f (\varepsilon_c + \varepsilon_{fr}) + E_m (1 - V_f) (\varepsilon_c + \varepsilon_{mr}) \quad (\sigma_m < \sigma_y) \quad (7-1)$$

$$\sigma_c = E_f V_f (\varepsilon_c + \varepsilon_{fr}) + (1 - V_f) \{K(\varepsilon_c + \varepsilon_{mr})^n\} \quad (\sigma_m > \sigma_y) \quad (7-2)$$

where E is elastic modulus, while ε and σ show strain and stress, respectively. Also, the subscripts f, m, c, y, and r mean fiber, matrix, composite, yield, and residual, respectively. The tension stress and the compression stress are indicated by marking with plus or minus sign. Besides, parameters used in the ROM for the calculation analysis are shown in Table 3.

3. Results and discussion

3.1. Residual stress of the SiC/Al composites

The diagrams of $2\theta - \sin^2\psi$ for three typical post-treatments were shown in Figure 2. It can be seen that there is a good linear relationship between 2θ and $\sin^2\psi$. The residual stress was calculated by substituting the slope of curve to Equation (1). According to Equation (1), it can be known from Figure 2 that residual stress will be increased when the slope becomes greater; besides, the slope of curve has reverse sign with the residual stress, in other words, negative sign of the slope of the curve means tension stress.

The residual stresses along the fiber direction and the right angle direction for each post-treatment specimen were obtained and shown in Table 4. It can be found that the value of the residual stress along the fiber direction was much greater than that along the right angle direction; besides, the value of the residual stresses was increased as the

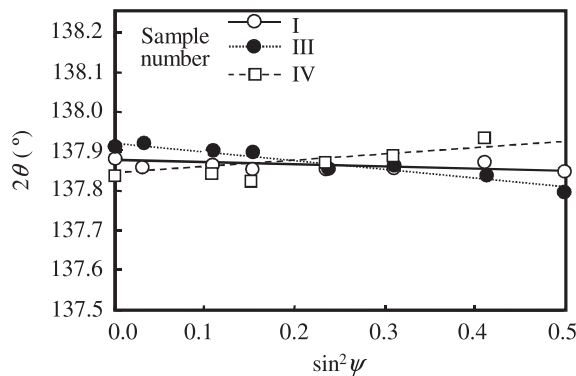
Figure 2. The relationship between 2θ and $\sin^2\psi$.

Table 4. Post-treatments and the relative residual stress of the SiC/Al composites.

Sample number	Post-treatments	Residual stress (MPa)	
		The fiber direction	The right angle direction
I	823 K \times 5 min annealed	11.2	3.9
II	823 K \times 5 min air cooling	20.6	4.7
III	823 K \times 5 min water quenched	41.8	12.4
IV	77 K \times 10 min sub-zero treated	−35.5	−17.7
V	176 K \times 10 min sub-zero treated	−18.8	−5.4
VI	Pre-loading (95.9 MPa)	−34.3	1.5

cooling rates during post-treatments increased from 11.2 to 41.8 MPa for heat treatment and from −18.8 to −35.5 MPa for sub-zero treatment. Also, it is noticeable that the residual stresses of the some specimens were higher than the yield stress (about 30 MPa) of the Al matrix.

In the cases of heat and sub-zero treatments, it is easy to understand that the residual stress originated in different thermal expansion behavior between the fiber and matrix. The larger the difference of thermal expansion coefficients between the Al matrix and SiC fiber, the greater the residual stress produced in the post-treatments. While in the case of pre-loading, the residual stress should result from the plastic deformation of the Al matrix and the elastic recovery of the SiC fiber.

3.2. Effect of the residual stress on tensile behaviors based on experiments

Figure 3 represents a stress–strain curve of the SiC/Al composites from the tensile tests. There is a point on the curve, at which the slope had a sudden change due to the yield of the SiC/Al composite during the tensile test.

To find the effect of the residual stress on the tensile behaviors during the tensile tests, the composite stresses were read out from strain–stress curve at the point of the SiC/Al composite yield, the strain of 0.1, 0.2, 0.5%, and the ultimate tensile strength of the SiC/Al composite for each of post-treatment specimens. The relationship between residual stress and tensile stress is shown in Figure 4. It was found that there was an approximately linear relationship between the tensile stress and the residual stress in the case of the same strain condition; besides, the residual stress has different influence on

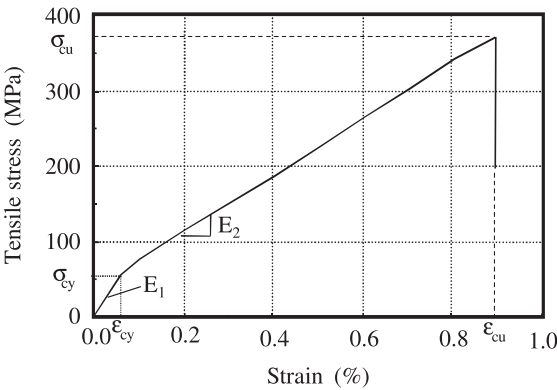


Figure 3. The stress–strain curve of the SiC/Al composites from the tensile test of the sample IV.

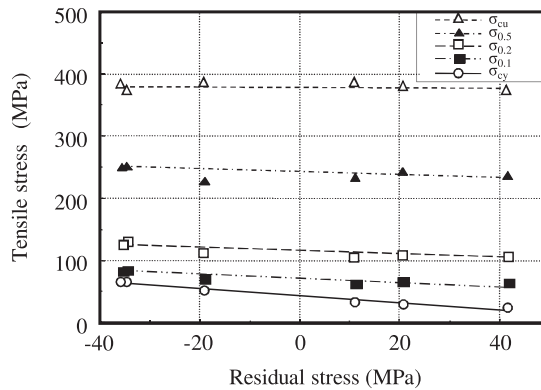


Figure 4. The relationship between residual stress and tensile stresses of the SiC/Al composites during the tensile tests.

the tensile stress of the SiC/Al composite at different tensile stress conditions. To be exact, the residual stress had a great influence on the tensile stress when the tensile stress of the SiC/Al composite is relatively small. Minus residual stress can increase tensile stress while plus one can decrease tensile stress of the SiC/Al composite. For example, the residual stress of -35 MPa can increase the tensile stress by about 20 MPa for the σ_{cy} . However, the influence went down with the increase in tensile stress and almost disappeared for the ultimate tensile strength of the SiC/Al composite (σ_{cu}). In this condition, the effect of the residual stress on the tensile behavior can be neglected.

3.3. Effect of residual stress on tensile behaviors based on the ROM

The ROM taking the residual stress into account was used to analyze the effect of the residual stress on the tensile behaviors of the SiC/Al composite. Figure 5 shows the stress–strain curve of the SiC/Al composite for the sample IV from the ROM calculation. Comparing with Figure 3, it can be found that both the stress–strain curves from the tensile tests and the calculation based on the ROM are very similar with each other.

The relationship between the residual stress and the tensile stress of the SiC/Al composite obtained from the ROM is shown in Figure 6. Also, both the relationship between the residual stress and the tensile stress of the SiC/Al composite from the tensile test and the calculation from the ROM are compared. From the comparison, it can be found that

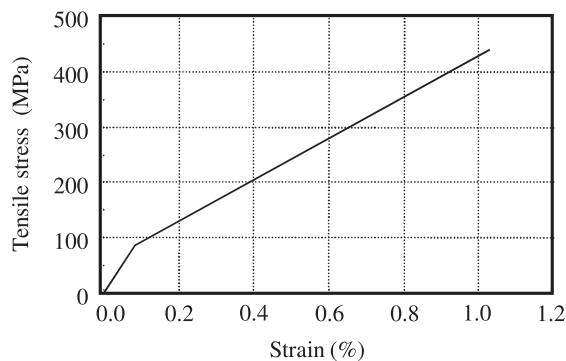


Figure 5. The stress–strain curve of the sample IV from the ROM calculation.

both of them are also very similar. However, the values of tensile stress from the ROM were larger than these from the tensile tests. It should be due to the heterogeneous distribution of the fibers (Figure 1(a)) and other influencing parameters.

Based on the above results, it can be concluded that the present calculation analysis based on the ROM is a simple and effective method to evaluate the effect of the residual stress on the tensile behavior of the SiC/Al composite. Also, it can be confirmed that the effect of the residual stress on tensile stress of the SiC/Al composite is restricted in the region of small stress and decreased as tensile stress of the SiC/Al composite increased. It can be considered that the influence of the residual stress on the tensile stress of the composite is compensated by the tensile test. For the ultimate tensile strength, the effect of the residual stress can be neglected.

As shown in Figure 3 above, E_1 and E_2 represent Young's modulus of the composite before and after the yield, respectively. Figure 7 shows the relationship between the residual stress and Young's modulus of the SiC/Al composite. From the figure, it can

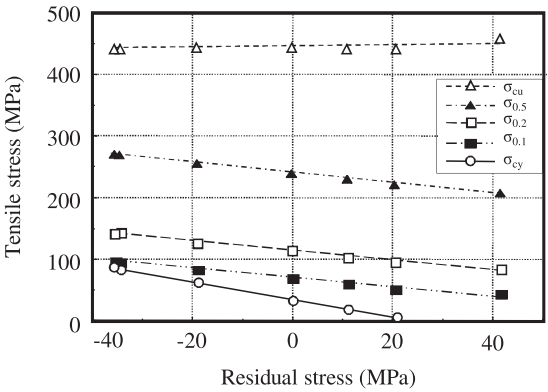


Figure 6. The relationship between residual stress and tensile stresses of the SiC/Al composites from the ROM calculation.

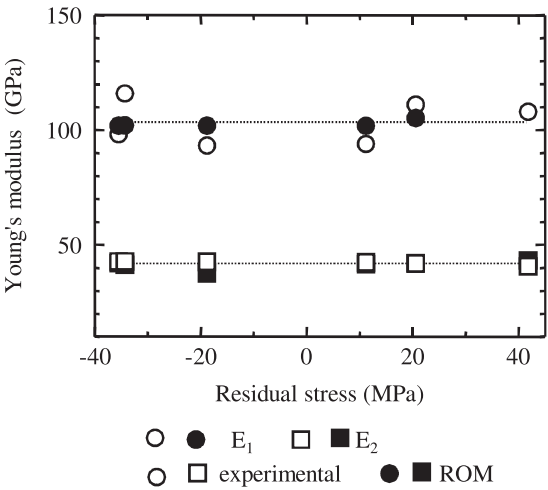


Figure 7. The relationship between the residual stress and Young's modulus of the SiC/Al composites.

be seen that the slopes of the curves of E_1 and E_2 were zero. That means Young's modulus did not change as the residual stress changed, in other words, the residual stress almost had no influence on Young's modulus of the SiC/Al composite. Besides, the calculation result from the ROM also agreed with that from the tensile tests.

4. Conclusions

The experimental results revealed that the residual stress had a great influence on the tensile stress when the tensile stress was small; however, the influence decreased as tensile stress increased and finally almost disappeared at the ultimate tensile strength of the SiC/Al composite. Compressive residual stress can increase tensile stress, and tensile residual stress can decrease tensile stress. Furthermore, the effect of the residual stress on Young's modulus of the SiC/Al composite was found to be very small.

The calculation analysis based on the ROM taking the residuals stress into account was in almost total agreement with the results obtained from the tensile tests. It can be confirmed that the calculation analysis based on the improved ROM is a simple and effective method to evaluate the effect of the residual stress on the tensile behaviors of the SiC/Al composite.

Acknowledgement

The authors would like to thank to Fujikara Co., Ltd, in Japan for its financial support.

Reference

- [1] Chun HJ, Wooh SC, Daniel IM. Residual thermal stresses in a filamentary SiC/Al composite. *Compos. Eng.* 1995;5:425–436.
- [2] Quek MY. Analysis of residual stress in a single fibre-matrix composite. *Int. J. Adhes. Adhes.* 2004;24:379–388.
- [3] Jiang ZH, Li GY, Lian JS, Ding XD, Sun J. Elastic-plastic stress transfer in short fibre-reinforced metal-matrix composites. *Compos. Sci. Technol.* 2004;64:1661–1670.
- [4] Gasparyan S. Determination of residual stresses in metallic composites. *J. Mater. Process. Technol.* 2006;178:14–18.
- [5] Güngör S. Residual stress measurements in fibre reinforced titanium alloy composites. *Acta Mater.* 2002;50:2053–2073.
- [6] Choo H, Bourke MM, Daymond MR. A finite-element analysis of the inelastic relaxation of thermal residual stress in continuous-fiber-reinforced composites. *Compos. Sci. Technol.* 2001;61:1757–1772.
- [7] Akser EO, Choy KL. Finite element analysis of the stress distribution in a thermally and transversely loaded Ti-6Al-4V/SiC Fibre composite. *Compos. Part A-Appl. Sci.* 2001;32:243–251.
- [8] Li XB, Zou HM, Pan J. A study of interfacial residual stress field in a $K_2O \cdot 6TiO_2$ /Al composite by LACBED and 3-D finite element method. *Mater. Sci. Eng. A-Struct.* 2001;308:65–73.
- [9] Huang B, Yang YQ, Luo HJ, Yuan MN. Effects of the coating system and interfacial region thickness on the thermal residual stress in SiC/Ti-6Al-4V composites. *Mater. Des.* 2009;30:718–722.
- [10] Jensen HM. Residual stress effects on the compressive strength of uni-directional fibre composites. *Acta Mater.* 2002;50:2895–2904.
- [11] Fernández P, Fernández R, González-Doncel G, Bruno G. Correlation between matrix residual stress and composite yield strength in PM 6061Al-15vol% SiC_w. *Scr. Mater.* 2005;52:793–797.
- [12] Fei WD, Hu M, Yao CK. Effects of thermal residual stress creeping on microstructure and tensile properties of SiC whisker reinforced aluminum matrix composite. *Mater. Sci. Eng. A-Struct.* 2003;356:17–22.