EFFECT OF THE MATRIX PROPERTIES ON THE STRENGTH AND RELIABILITY OF FIBER REINFORCED METALS COMPOSITE

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SUMMARY: In this study, a Monte-Carlo simulation based on the elastic-plastic finite element method was carried out for estimating effect of matrix property on the strength and reliability of composite. The results showed that if yield stress or work hardening of the matrix decreased, composite strength decreased and the strength scatter increased. The decrease of composite strength is related to the reduction of the reinforced efficiency of fiber. At the same time, count of accumulated fiber-break is reduced when yield stress or work hardening of the matrix decreased. It can be concluded that the fiber fracture process is closely related to the strength and reliability of composite.

KEYWORDS: Fiber Reinforced Metals, Tensile Strength, Reliability, Monte-Carlo Simulation, Finite Element Method, Fracture Process, Weibull Distribution.

INTRODUCTION

Fiber reinforced metal composites are expected to use as structural materials in various applications, owing to their good mechanical properties such as specific strength, specific modulus, high temperature strength and so on. The mechanical properties of the matrix will be changed at an elevated temperature and after undergoing some heat process. How the matrix mechanical property influences the strength and reliability of composite is very important in the practical use. To investigate the effect of matrix property on the strength and its scatter of composite, tensile test has been performed under elevated temperature and after heat treatment for SiC/Al-alloy composites[1-3]. It has been clarified that the composite strength decreases but the scatter increases while the matrix becomes weak. The strength and its scatter are related to fracture process of composite[4-5]. However, the studies have been restricted to investigate only the influence of the matrix properties experimentally, removing the influences such as the reaction in the interface perfectly.

In this study, a Monte-Carlo simulation based on the elastic-plastic finite element method was carried out for estimating the effect of matrix property on the strength and reliability of the composite. Finally, it was discussed relating to the fracture process.

MODEL AND TECHNIQUE OF THE SIMULATION

The finite element model and mesh in the present study are shown in Fig. 1. The simulation model, it is built on a unidirectional fiber reinforced metal monolayer plate including 10 fibers. The two one-dimensional line elements representing the reinforcing fibers are incorporated into two sides along the y-axis of a 4-nodes isoparametric element (plane stress), which represents the metal matrix. The model is divided into 20 elements in y-axis. Y-axis of nodes in the lower side is fixed, but displacement increment is given along y-axis of nodes in the upper side. The strength of fiber elements is given from Weibull random numbers, using an inverse function of Weibull distribution. Furthermore, for exactly estimating reasonably each element stress increment necessary to the fiber break, the r_{min} method is applied to the simulation procedure[6].

The fibers are regarded as elastic state but the matrix is assumed to be elastic-plastic. Fiber element is considered to break when the stress, which is along the axial direction of the fiber, reaches the strength of that fiber element. After a fiber element breaks, the stiffness will be changed to zero. The axial load, which is loading on that fiber element, is decreased to zero by dividing the load into 15 times. When composite stress decreases below 70% of the maximum stress, the composite is considered to be failure, and then the simulation will be ended. The flow chart of the present simulation is shown in Fig.2.

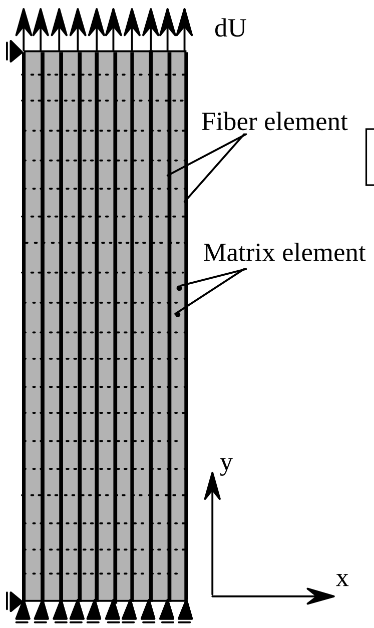

Fig.1 Finite element model and mesh.

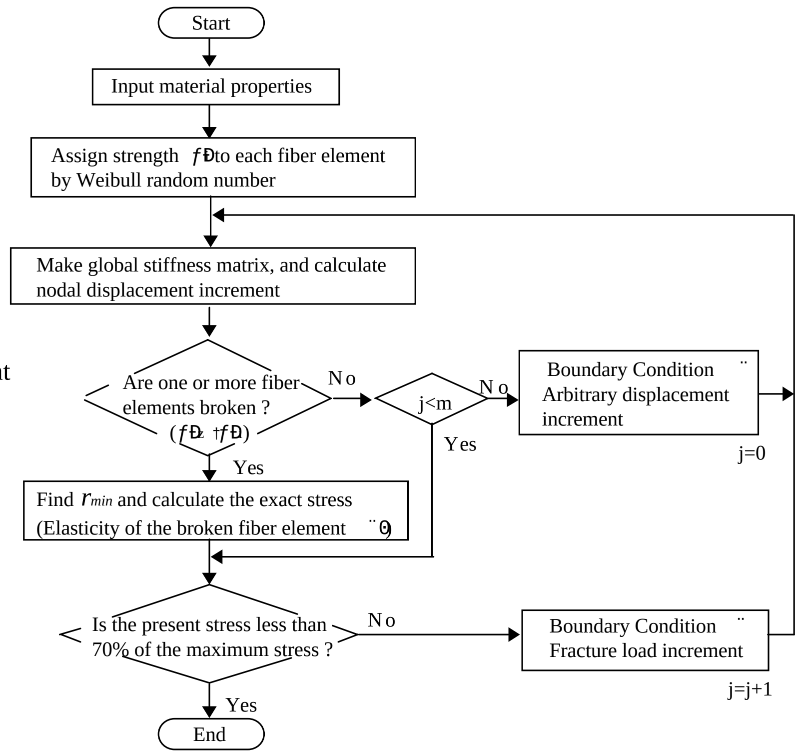

Fig.2 Flow chart of the present simulation .

This simulation was carried out 50 times for SiC/Al and B/Al composites on each condition of the matrix property, respectively. Composite strength and its scatter were evaluated using Weibull distribution. The parameters obtained by tensile test of pure aluminum and the fibers extracted from SiC/Al and B/Al, were used as mechanical property parameters in this simulation. The parameters are shown in Table 1. The gauge length was set as 10mm and 30mm for SiC/Al and B/Al composites, respectively. To investigate the effect of weakening or strengthening of the matrix on composite strength and reliability, four sets (Type C-1, C-2, C-3 and C-4) of yield stress and work hardening rate were established based on those of pure aluminum ones (Type R) as shown in Table 2.

Table 1 Material constants used in the present simulation.

Assumed composite	SiC/Al	B/Al
Diameter of fiber (mm)	0.014	0.14
Elastic modulus of SiC fiber (GPa)	198	392
Weibull shape parameter of fiber strength *m*	3.2	16.3
Weibull scale parameter of fiber strength (GPa)	2.41	3.97
Standard gauge length (mm)	10	30
Distance between fiber (mm)	0.014	0.14
Element length of fiber (mm)	0.5	1.5
Elastic modulus of matrix (GPa)	68.6	68.6
Poisson's ratio of matrix	0.33	0.33
Thickness of composite (mm)	0.014	0.25
Volume fraction of SiC fiber (%)	35.7	32.8

Table 2 Property of the matrix used in the present simulation.

Type	Yield stress of matrix ƒÐ$_y$ (MPa)	Work hardening rate H' (MPa)
R	52.2	620.5
C-1	104.4	1241.1
C-2	26.1	310.3
C-3	10.5	124.1
C-4	5.2	62.1

SIMULATION RESULTS

Strength and Its Scatter of the Composites

A stress-strain curve of SiC/Al composite is shown in Fig.3. From this figure, it can be seen that the slope of the curve has a change due to yielding of the matrix. Till the maximum stress

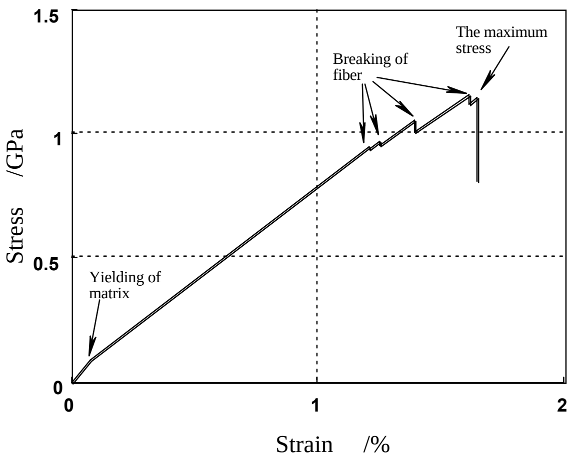

Fig.3 A stress-strain curve of SiC/Al composite.

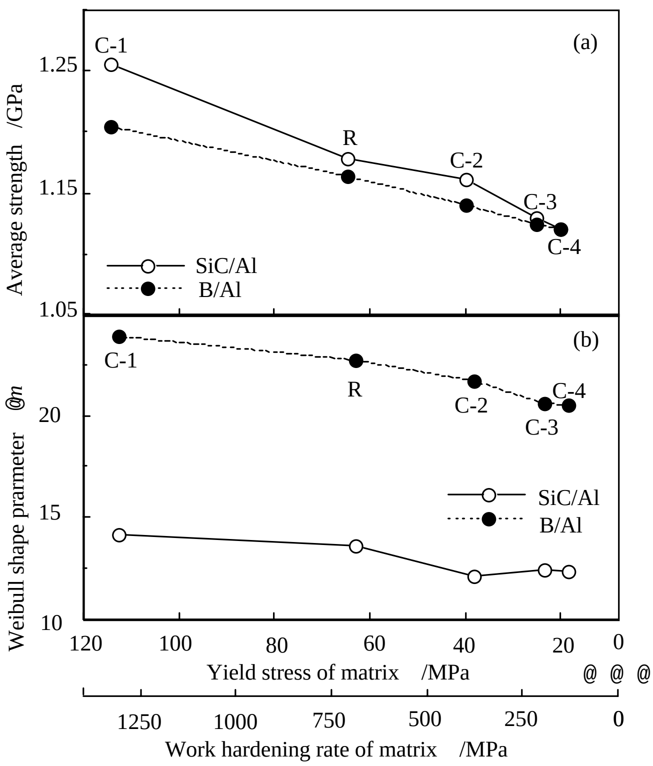

Fig.4 Average strength and Weibull shape prarmeters of SiC/Al and B/Al composites.

(composite strength), there are abrupt changes of the stress at some times on the curve. The abrupt stress changes are considered to be owing to breaking of the fibers in the composite. Tensile strength and Weibull shape parameter of SiC/Al and B/Al composites are shown in Fig. 4. Composite strength decreases with the decrease of yield stress or work hardening rate of the matrix for the tow composites, that is, with weakening of the matrix (see Fig.4a). The ratio of the strength degradation to the yield stress change has been estimated by the rule of mixture (ROM) as follow in the case of SiC/Al composite.

$$\sigma_{rom} = \sigma_f V_f + \sigma_m(1-V_f) \qquad (1)$$

Where, σ_f is the fiber strength, V_f is fiber volume fraction (38.7%) and σ_m corresponds to the matrix stress when the composite breaks. In the present study, the strength of extracted fiber from SiC/Al composite (2.2GPa) is used as σ_f, Yield stress (σ_y) of the matrix shown in Table 2 is used as σ_m . The ratio (σ_c/σ_y) for the present simulation was 1.36, about 2 times as large as that (about 0.61) given by the rule of mixture. It means that effect of matrix strength on composite strength is larger than estimation of the rule of mixture. In addition, Weibull shape parameter *m* decreases, that is, the scatter become wide with the decrease of yield stress or work hardening rate (see Fig.4b). The above relationship between composite strength, Weibull shape parameter and the change of the matrix property has been shown in the cases of hardening or weakening of the matrix under elevated temperature and after heat treatment for SiC/Al-alloy composites experimentally[1-3].

Fracture Process and ineffective length

It can be considered that the weak fibers will break at first, comparing with the strong ones during loading in the composite. Till the maximum stress, some breaking of the fiber in the composite will happen during loading as shown in Fig.3. The relationship between the strength of the composite, its scatter and the fracture process has been discussed in the present study. By calculating average count of the accumulated broken fiber element after reading out the counts of breaking fiber during loading in the present simulation, relationship between average count of broken fiber and the property of the matrix for case of SiC/Al composite is shown in Fig. 5. Average count of broken fiber element go down along with decreasing yield stress or work hardening rate of matrix, that is, with weakening of the matrix. It is hinted that the strength and its scatter of the composite relate with the accumulation of the fiber breaking in the composite comparing the results of Fig.4 and Fig.5.

Further, in order to discuss the effect of the accumulation of fiber breaking, the stress of the composite was read out when the fiber break in breaking fiber order for all specimens. Then the average composite stress and Weibull shape parameter *m* were calculated by Weibull distribution for each fiber breaking. Fig.6 shows the number of broken fiber and the average composite stress and Weibull shape parameter. The average composite stress and Weibull shape parameter increase with number of broken fiber. That is, the more the accumulating fiber fractures is, the higher stress needed for the fracture of composite is, and the lower the stress scatter is. Therefore, the more the accumulating fiber fracture is, it becomes more obvious that composite strength is controlled by the stress which has a high value and low scatter. From the results mentioned above, it is clarified that composite strength and reliability are related closely with the accumulation of breaking fiber.

Finally, stress distribution has been calculated by giving tensile strength (SiC/Al: 2.16GPa, B/Al: 3.14GPa) of extracted fiber to the center fiber element, and giving a large strength value (100GPa) to other fiber elements in the present simulation. Ineffective length has been calculated from the stress distribution along a broken fiber in the composites, according to the hypothesis that ineffective length is 2 times of the length, in which stress

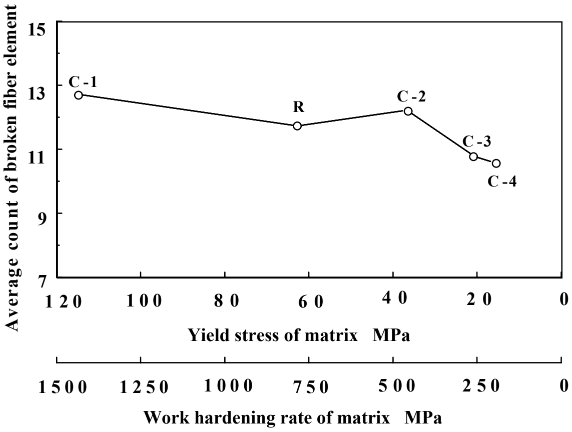

Fig.5 Average count of broken fiber element vs the matrix property of SiC/Al composite.

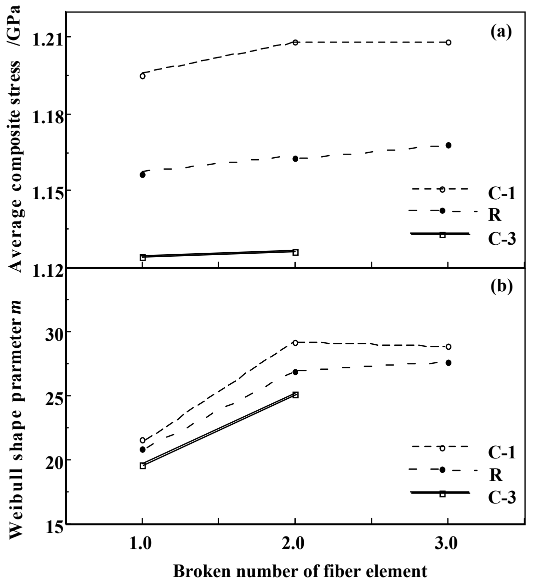

Fig.6 Number of broken fiber vs composite stress and Weibu shape parameter of B/Al composite

recovers to 90% of the stress level before fiber breaking. The results are illustrated in Fig. 7. From this figure, the ineffective length becomes short with the increase of yield stress or work hardening rate. That is, the fiber region that can not contribute to composite strength enlarges by matrix weakening. It means that reinforced efficiency of the fiber is reduced. It was given from the above results that effect of matrix strength on composite strength is larger than estimation of the rule of mixture. It can be that the contribution of the matrix property for composite has not only a simple addition by the rule of mixture, but also has an effect on the fiber reinforced efficiency in composite.

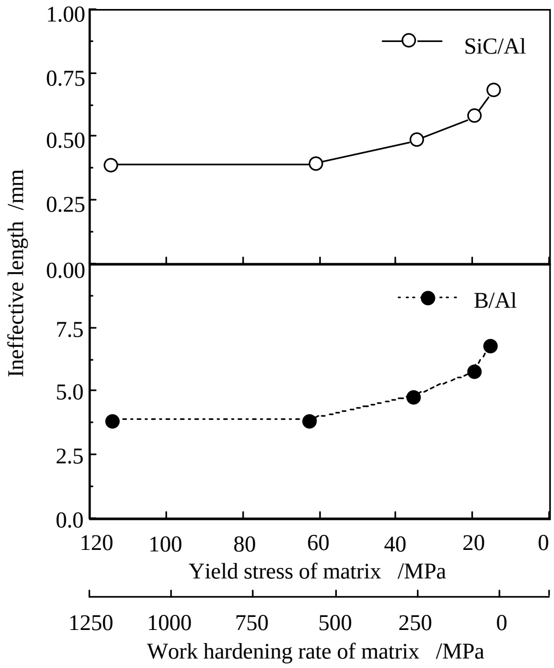

Fig.7 Ineffective length of fiber in SiC/Al and B/Al composites.

CONCLUSIONS

A Monte-Carlo simulation based on the elastic-plastic finite element method was carried out for estimating effect of matrix property on composite strength and its reliability of composite. The results showed that if yield stress or work hardening of the matrix decreased, composite strength decreased and the strength scatter increased. The decrease of composite strength is related to the reduction of the reinforced efficiency of fiber. At the same time, the number of accumulated fiber-break is reduced with the matrix weakening. It can be concluded that the fiber fracture process is closely related with the strength and reliability.

REFERENCES

1. Yun LU, FUKUNAGA, H. and HIROHASHI, M., “Tensile strength and Its Scatter of SiC/Al-alloy Composite Wire at Elevated Temperature”, *Proceeding of 39th Materials Incorporated meeting of the Japan Scientific Meeting*, 1995, pp.131-132.
2. FUKUNAGA, H. and Yun LU, “Tensile Strength of SiC/Al Alloy Composite Wires Considering Strength of Fiber Embedded in Matrix”, *Transactions of the Japan Society of Mechanical Engineers*, Vol.57A, No.544, 1991, pp3023-3027.
3. FUKUNAGA, H., GODA, K. and Yun LU, “Effect of Heat Treatment on Strength and Its Scatter of SiC/Al Alloy Composite Wires”, *Transactions of the Japan Society of Mechanical Engineers*, Vol.57A, No.535, 1991, pp536-541.
4. Yun LU and FUKUNAGA, H., “The Scatter of Strength and Fracture Behavior of Unidirectional FRM”, *Proceeding of The 71st JSME Fall Annual Meeting*, Vol.B, pp.138-140.
5. Yun LU, HIROHASHI, M., ASANUMA, H. and ARAOKA, K., “Fracture Process and Scatter of Strength for Unidirectional Reinforced SiC/Al Composites”, *Proceeding of The 72nd JSME Spring Annual Meeting*, Vol.II, pp.608-609.
6. K. Washizu, H. Miyamoto, Y. Yamata, Y. Yamamoto and T. Kawai, *Handbook of Finite Element Method*, Baifukan Ltd., Japan, 1992.