BENDING STRENGTH OF Fe-Mn-Si-Cr SHAPE MEMORY ALLOY MACHINING CHIPS REINFORCED SMART COMPOSITE

Yoshimi Watanabe*, Teppei Wakatsuki ** , Hisashi Sato*, Tadakatsu Maruyama***
*** Omohi College, Nagoya Institute of Technology**
**** Graduate Student, Department of Engineering Physics, Electronics and Mechanics**
Nagoya Institute of Technology
*****Awaji Materia CO., LTD.**

Keywords: *smart material, Fe-Mn-Si-Cr shape memory alloy (SMA), machining chip, coil, plaster, residual stress, three-point bending test*

Abstract

This paper reports the fabrication method and mechanical properties of a shape memory alloy (SMA) machining chips / plaster smart composite, which can be used in architectural and civil engineering applications. Fe-Mn-Si-Cr SMA machining chips are subjected to pretensile strain at room temperature, and are embedded into plaster matrix. The Fe-Mn-Si-Cr SMA machining chips / plaster composites are then heated up. Three-point bending test is performed for the mechanical property characterization. Fe-Mn-Si-Cr SMA coils / plaster composites using SMA fibers are also fabricated and mechanical tested as model material. SMA machining chips have the property of shape recovery regardless of its heavy deformation due to machining. Therefore, SMA machining chips are available for reinforcement material as well as SMA fiber. It is found that SMA machining chips with prestrain improve the bending strength of composite. By using the Fe-Mn-Si-Cr SMA machining chips for the reinforcement of the composite, one can obtain materials for practical engineering applications at low cost.

1 Introduction

It is known that the residual stress of composite influences the mechanical properties of the composite, where the residual stress in the composite is mainly caused by the mismatch of the thermal expansion coefficient between the matrix and reinforcement, when the composite fabricated at high temperature is cooled down to room temperature [1, 2]. If the composites are reinforced by shape memory alloy (SMA) fiber that shrinks in the matrix, the mechanical properties of composites will be improved significantly.

Recently, much attention has been paid to the development of SMA composites [3-5]. For example, Furuya *et al*. [3] have proposed a design concept of NiTi SMA fiber / Al composite. Mechanical properties of NiTi SMA fiber / CFRP have been studied by Jang *et al*. [5] The motivation of this research is to develop an SMA fiber / plaster composite which will be commercially applicable for architectural and civil engineering materials applications. For this purpose, the NiTi SMA is not suited, since the NiTi SMA is unacceptably expensive.

In our previous studies, we have studied the fabrication method and mechanical properties of Fe-Mn-Si-Cr SMA [6, 7] fiber / plaster composite [8-11]. The fabrication process and the strengthening mechanism of a plaster matrix composite by use of the shape memory effect of the Fe-Mn-Si-Cr alloy are summarized in Fig. 1 [8]. Shape memory treatment was given to the Fe-Mn-Si-Cr SMA fibers in order to memorize the straight shape (Fig. 1 (a)). The SMA fibers were subjected to pretensile strain at room temperature (below the Md temperature) (Fig. 1 (b)). The SMA fibers were embedded into plaster plus water matrix (Fig. 1 (c)). The SMA fiber / plaster composites were heated to 250 °C (above As) to generate the compressive residual stress in the matrix along the fiber axis (Fig. 1 (d)). It has been found that the shape memory effect of the embedded straight and wavy SMA fibers enhances the strength and energy absorption prior to fracture of the composites, where the embedded SMA fibers shrink due to their shape memory effect

[8]. It is also found that bending fracture load and energy dissipated for fracture were improved significantly for the wavy Fe-Mn-Si-Cr SMA fiber reinforced smart composites [9-11].

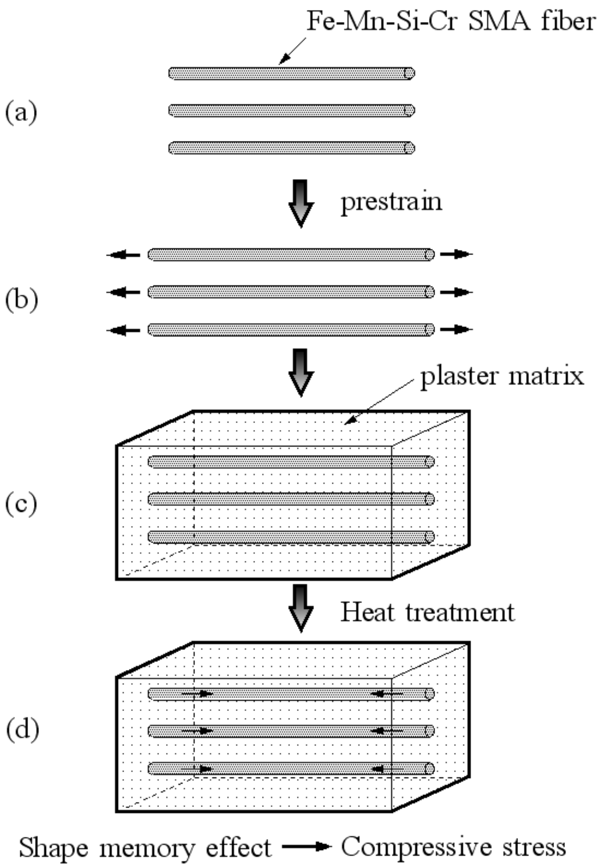

Fig. 1 Design concept of the Fe-Mn-Si-Cr SMA fiber / plaster matrix composite.

Meanwhile, one of the main industrial applications of Fe-Mn-Si-Cr SMA is pipe joining of steel pipes in civil engineering constructions. Figure 2 shows schematic illustrations of SMA pipe joint. As can be seen, a lot of Fe-Mn-Si-Cr SMA machining chips are generated during the fabrication of SMA pipe joint. Figure 3 shows macrographs of Fe-Mn-Si-Cr SMA machining chips.

In this article, therefore, fabrication method and mechanical properties of Fe-Mn-Si-Cr SMA machining chips reinforced smart composites are studied. The smart composites consist of SMA machining chips and plaster matrix. Because SMA machining machining chips are used as its reinforcements, the smart material can be treated as ecomaterial.

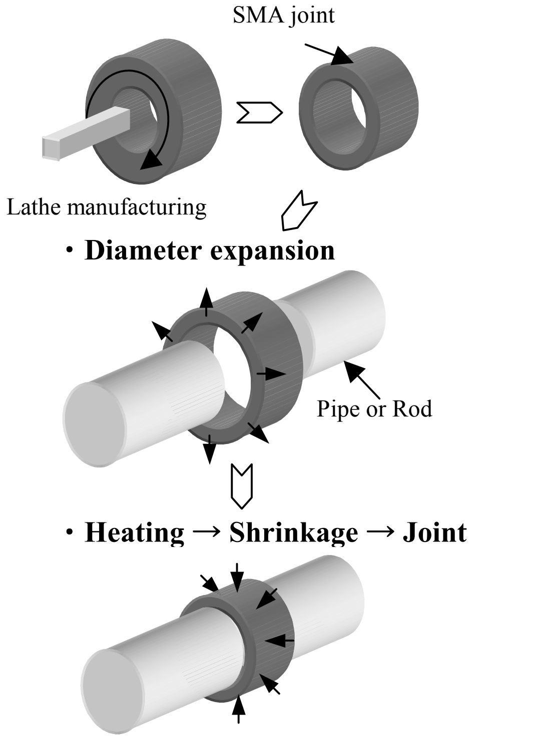

Fig. 2 Schematic illustrations showing SMA joint.

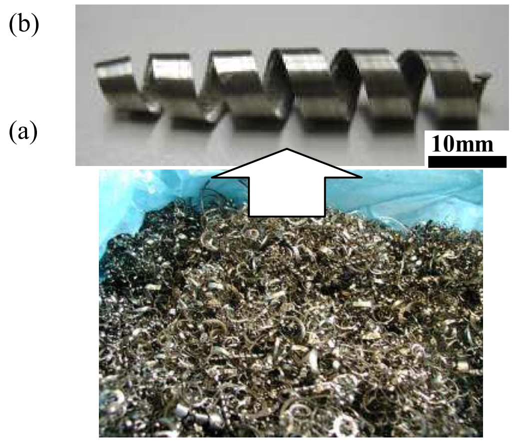

Fig.3 (a) Fe-Mn-Si-Cr SMA machining chips and (b) a chip used in the present experiment.

2 Fe-Mn-Si-Cr SMA

It is known that some Fe-Mn-Si alloys with suitable composition exhibit a good shape memory effect of a one-way type with the temperature hysteresis as large as 500 °C, governed by the fcc (γ) <-> hcp (ε) transformation [6]. Fe-Mn-Si alloys appear to be commercially applicable owing to their inexpensiveness and excellent workability. With addition of Cr, it is possible to achieve a good corrosion resistance, which enhances commercial significance to this type of alloy [12, 13]. Tsuzaki *et al*. [14] have found that addition of 0.3 wt% carbon to the Fe–17Mn–6Si alloy causes the further increase of shape memory effect. The cost of Fe-Mn-Si-Cr SMA fiber with 1.0mm diameter is 170 yen/m, whereas that of available NiTi SMA fiber is 1400 yen/m (without shape memory treatment) or 2200 yen/m (with shape memory treatment) [9]. In this way, the fiber used here is much less expensive than NiTi SMA fiber. Therefore, by using the Fe-Mn-Si or Fe-Mn-Si-Cr SMA for reinforcement of the SMA composite, one can produce practically and economically sounded engineering materials. Table 1 shows mechanical property of Fe-27.80mass%Mn-5.97mass%Si-4.93mass%Cr SMA.

Table 1 Mechanical property of Fe-27.80Mn -5.97Si-4.93Cr SMA (mass%).

Yield Stress	MPa	334
Tensile Stress	MPa	760
Elongation	%	27
Young'sModulus	GPa	170
Poisson's ratio		0.359
Ms	^{o}C	-20～20
Af	^{o}C	130～185

3 Experimental Method

The composition (in mass %) of the SMA machining chips used in this investigation was of Fe -27.80Mn -5.97Si -4.93Cr. The machining chips with almost same shape (outer diameter: 4mm and length 30 mm) were subjected to heat treatment in air at 950 ^{o}C for 10 min, followed by air cooling to room temperature in order to obtain a single phase austenite microstructure (shape memory treatment). In order to assess the shape memory effect of the Fe-Mn-Si-Cr SMA machining chips used for the composite, the ratio of shape recovery versus annealing temperature curves were obtained. Tensile tests were carried out on a screw-driven test machine. Macroscopic tensile strains of 10% and 20% were given, respectively, at room temperature. To study the shape recovery during the machining, the machining chips without shape memory treatment are also used. Following the tensile deformation, each specimen was annealed at temperatures ranging from 100 ^{o}C to 350 ^{o}C for every interval 50 ^{o}C.

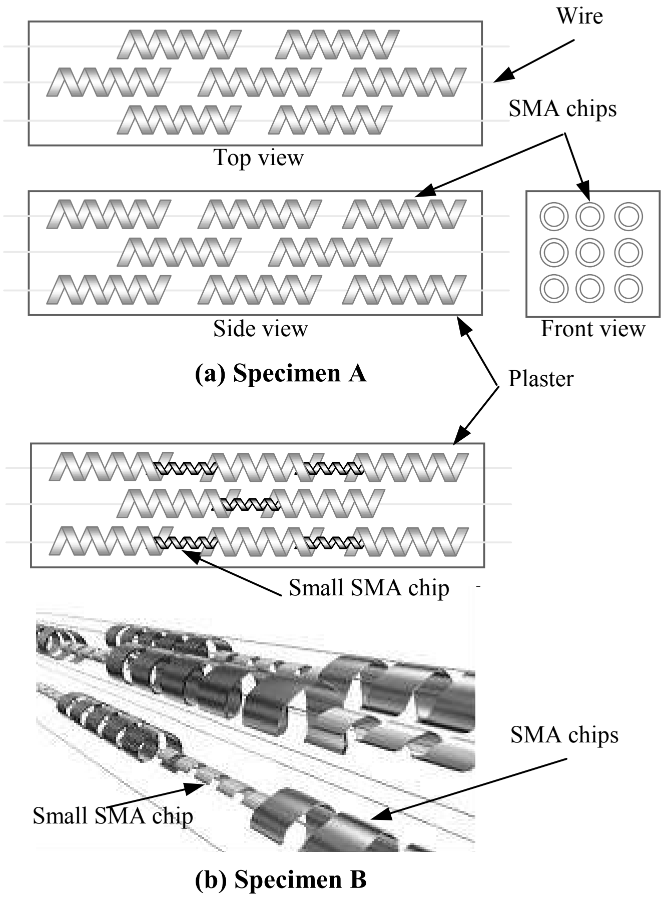

Fig. 4 Arrangement of SMA machining chips in (a) Specimen A and (b) Specimen B .

Fe-Mn-Si-Cr SMA machining chips subjected to pretensile strain at room temperature are embedded into plaster matrix. Arrangement of SMA machininge chips in (a) Specimen A and (b) Specimen B is shown in Fig. 4. In Specimen A, machining chips are discontinuously aligned; while they are continuously connected by small machining chips in Specimen B. These machining chips are supported by very narrow wires (0.09 mm in diameter), as shown in Fig. 4. The volume fraction of machining chips is 0.03. A schematic illustration of machining chips reinforced composite material was shown in Fig. 5. Since the humidity and the temperature have effects on the solidification of plaster [15], they were fixed to be 58 % and 20 ^{o}C, respectively, during the fabrication of composite. Specimens were dried at 20 ^{o}C for 2 days after solidification of the plaster matrix, and were kept in a dryer at 40 ^{o}C for 2 hours before the heat treatment [8,16]. The Fe-Mn-Si-Cr SMA machining chips / plaster composites are then heated up to 250℃ (above As) compressive residual stress in the matrix.

For the mechanical property characterization, a three-point bending test was performed using a screw-driven test machine at a crosshead speed of 2 mm/min. The span length of the bending test specimen was 60 mm. The specimen was loaded until fracture occurred, and bending strength was calculated from the load-stroke curves.

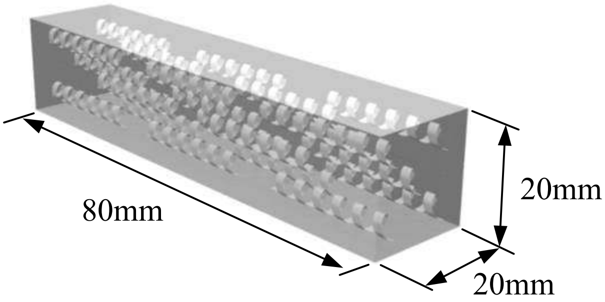

Fig. 5 A schematic illustration showing machining chips reinforced composite material.

4 Results and Discussion

4.1 Shape memory effect of Fe-Mn-Si-Cr SMA machining chips

Macroscopic shape recovery of SMA machining chips is shown in Fig. 6. It is important to note that SMA machining chips have the property of shape recovery regardless of its heavy deformation due to machining. Therefore, SMA machining chips are available for reinforcement material as well as SMA fiber.

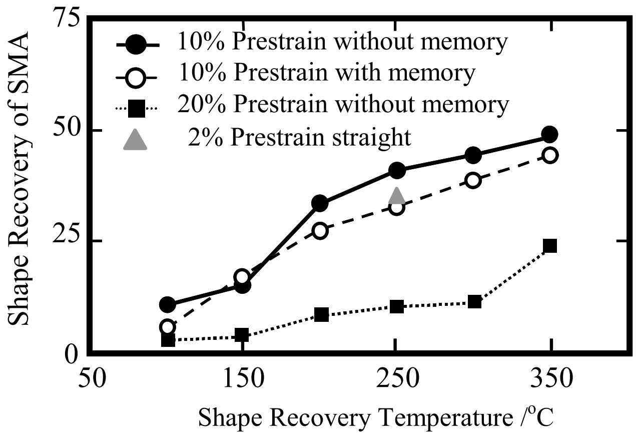

Fig. 6 Macroscopic shape recovery of SMA machining chips.

4.2 Fracture behavior of SMA machining chips / plaster composite

Figure 7 shows the fractured SMA machining ships / plaster composites after three-point bending test. Fracture behavior of plaster is also shown in this figure. As can be seen, many small cracks developed for Specimen B, whereas a few larger ones took place in the cases of Specimen A and plaster.

Figure 8 shows examples of bending load versus displacement curves for the plaster and composite samples. Since bending load of the composite with non-prestrain SMA machining chips always shows smaller value compared with that of the composite with prestrain SMA machining chips, we can conclude that the shape memory effect of SMA machining chips plays an important role on improvement of the fracture toughness of plaster. Note that the bending load of the plaster is equal to that of the plaster with wire. Therefore, the improvement of the bending strength does not occur by supporting wires themselves but by compressive residual stress introduced by shape memory effect of SMA machining chips.

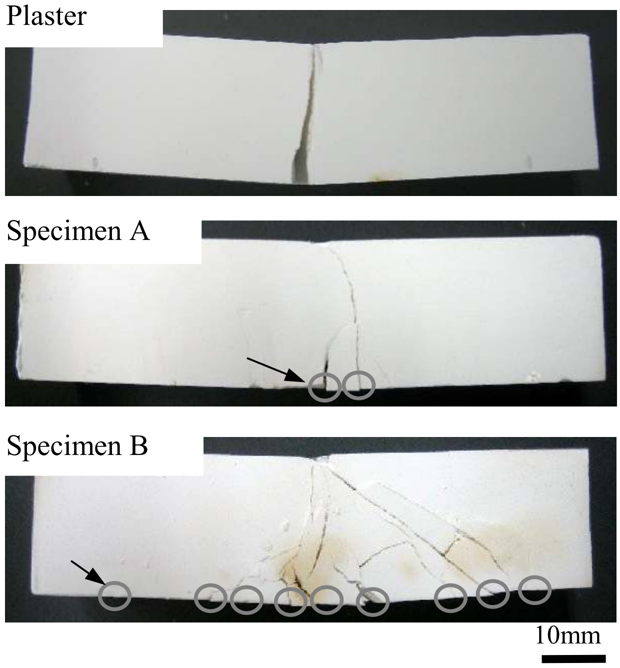

Fig. 7 Fracture behavior of the each SMA machining chips reinforced composite materials

Using these curves, the bending fracture strength can be evaluated and results are shown in Fig. 9. The bending fracture strength of the plaster specimen is also shown in this figure. The bending fracture strength of the Specimen A is less than about 1.5 MPa, although that of plaster is about 2 MPa. In this way, mechanical property of composite with discontinuous alignment of SMA machining chips is not good. This may be because there is a very high stress concentration near the machining chips with sharp edge, so the damage will initiate at the edge of the machining chips. On the other hand, it is noteworthy that the bending fracture strength of Specimen B is larger than that of plaster and Specimen A. In the case of Specimen B, since the machining chips are continuously connected by the smaller machining chips, large stress concentration near the machining chips will not occur. In fact, not a few larger crack but many small ones are observed for Specimen B. The development of many cracks enhanced the energy capability prior to the complete failure of the specimen [11].

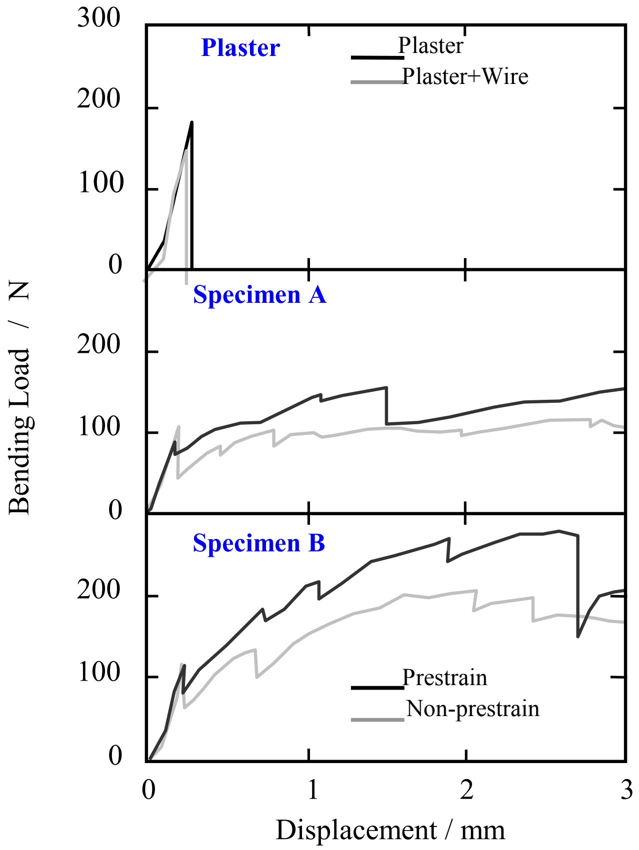

Fig. 8 Load-Displacement curves of SMA chips composites.

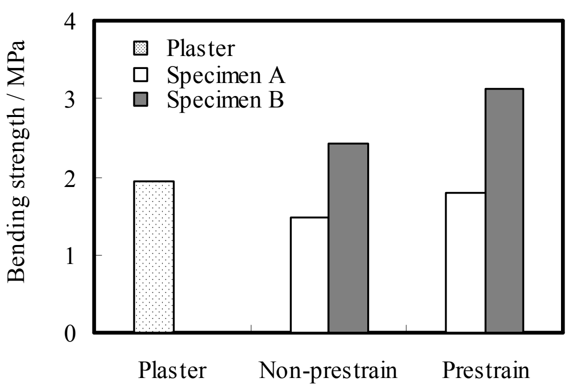

Fig. 9 Bending fracture strength of SMA machining chips reinforced composite materials.

4.3 Fracture behavior of SMA coils / plaster model composite

To discuss fracture behavior of Fe-Mn-Si-Cr SMA machining chips / plaster composites, Fe-Mn-Si-Cr SMA coils / plaster model composites using SMA fibers are also fabricated and mechanical tested as model material. Two types of model composites are used as shown in Fig. 10. In Model A, the SMA coils are discontinuously aligned as shown in Fig. 10 (a), and therefore this is an imitation of Specimen A. To imitate Specimen B, the continuous coils were used for Model B. The coils (outer diameter: 4.5 mm and inner diameter: 2.5 mm) are obtained from 1 mm diameter fiber, and are subjected to the shape memory treatment. Macroscopic tensile strain of 10% was given at room temperature.

The SMA coils, subjected to macroscopic pretensile strain of 10 %, are embedded into plaster matrix. The volume fraction of machining chips is 0.03. Three-point bending test was performed for these model composites.

Typical macrographs of Model A and Model B after three-point bending test is shown in Fig. 11. Typical bending load as a function of displacement curves are shown in Fig. 12.

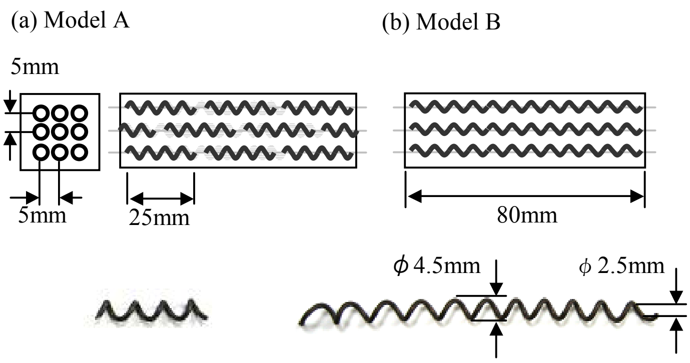

Fig. 10 Arrangement of coil shape SMA fibers.

The bending load of the composite with prestrain SMA coils always shows larger value compared with that of the composite with non-prestrain SMA coils. This is in agreement with the results obtained by SMA machining chips / plaster composites. Moreover, the bending strength of Model B is larger than that of Model A sample. Many small cracks were observed in Model B sample, whereas a few larger cracks are observed for Model A sample. In this way, we can obtain similar results by using the model composites.

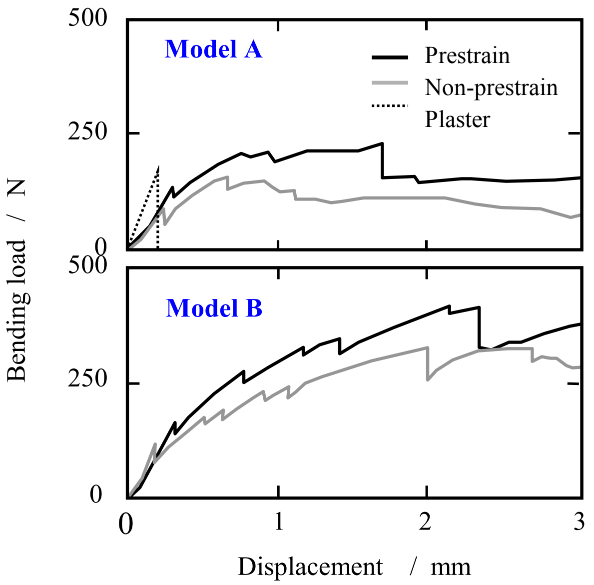

Fig. 11 Load-Displacement curves of Model specimens.

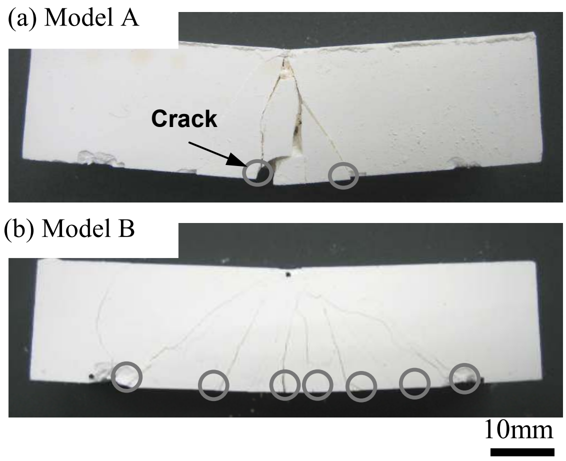

Fig. 12 Fracture behavior of specimen of (a) Model A and (b) Model B.

5 Conclusions

By using the Fe-Mn-Si-Cr SMA machining chips for the reinforcement of the SMA composite, one can obtain materials for practical engineering applications at low cost. This composite can be used in architectural and civil engineering applications.

References

[1] Wakashima K., Suzuki Y. and Umekawa S. "A Micromechanical Prediction of Initial Yield Surfaces of Unidirectional Composites". *J. Comp. Mater.* Vol.13, No. 4, pp 288 –302, 1979.

[2] Arsenault R. J. and Taya M. "Thermal residual stress in metal matrix composite". *Acta metal*. Vol. 35 pp 651-659, 1987.

[3] Furuya Y. "Design and material evaluation of shape memory composites". *J. Intell. Mater. Sys. Struc.* Vol. 7, pp 321-330, 1996.

[4] Berman J. B. and White S. R. "Theoretical modeling of residual and transformational stress in SMA composites". *Smart Mater. Struct*. Vol. 5, pp 731-743, 1996.

[5] Jang B.-K., Toyama N., Koo J.-H. and Kishi T. "Mechanical properties and manufacturing of TiNi/CFRP smart composites". *Inter. J. Mater. Prod. Tech.* Vol. 16, Nos. 1-3, 117-124, 2001.

[6] Sato A., Chishima E., Yamaji Y. and Mori T. "Orientation and Composition Dependencies of Shape Memory Effect in Fe-Mn-Si alloys". *Acta metal*. Vol. 32, No. 4, pp 539-547, 1984.

[7] Watanabe Y., Mori Y. and Sato A. "Training Effect in Fe-Mn-Si Shape-Memory Alloys". *J. Mater. Sci.,* Vol. 28, No. 6, pp 1509-1514, 1993.

[8] Watanabe Y., Miyazaki E. and Okada H. "Enhanced Mechanical Properties of Fe-Mn-Si-Cr Shape Memory Fiber / Plaster Smart Composite". *Mater. Trans*. Vol. 43, No. 5, pp 974-983, 2002.

[9] Watanabe Y., Miyazaki E. and Okada H. "Mechanical Properties of Wavy SMA Fibers Reinforced Smart Composite". *Trans. Mater. Res. Soc. Jpn*, Vol. 28, No. 3, pp 671-674, 2003.

[10] Wakatsuki T., Watanabe Y. and Okada H. "Development of Fe-Mn-Si-Cr Shape Memory Alloy Fiber Reinforced Plaster-based Smart Composites". *Materials Science Forum,* Vols. 475-479*,* pp 2063-2066, 2005.

[11] Tanaka S., Okada H., Watanabe Y. and Wakatsuki T. "Application of s-FEM to the Problems of Composite Materials with Initial Strain-like Terms". *Inter. J. Multiscale Computational Engineering*, Vol 4, No. 4, pp 411-428, 2006.

[12] Otsuka H., Yamada H., Maruyama T., Tanahashi H., Matsuda S. and, Murakami M. "Effects of Alloying Additions on Fe-Mn-Si Shape Memory Alloys". *ISIJ Int.* Vol. 30, No. 8, pp 647-679, 1990.

[13] Jiang B. H., Sun L., Li R. and Hsu T. Y. "Influence of austenite grain size on γ-martensitic transformation temperature in Fe-Mn-Si-Cr alloys" *Scripta Metall. Mater*. Vo. 33, No. 1, pp 63-68, 1995.

[14] Tsuzaki K., Natsume Y., Kurokawa Y. and Maki T. "Improvement of the shape memory effect in Fe-Mn-Si alloys by the addition of carbon". *Scripta Metall Mater,* Vo. 27, No. 4, pp 471-473, 1992.

[15] The Society of Gypsum and Lime, Japan (Eds.), "*Handbook of gypsum and Lime".* Gihodo Shuppan Co., Ltd., 1972.

[16] Watanabe, Y., Kawamoto A. and Matsuda K. "Particle Size Distributions of Functionally Graded Materials Fabricated by Centrifugal Solid-Particle Method", *Comp. Sci. and Tech.,* Vol. 62, No. 6, pp 881-888, 2002.