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Process and Mechanical Properties of Smart 6061Al Matrix Composite by Vacuum Hot Pressing

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Vacuum Hot Pressing에 의한 6061Al기지 지적복합재료의 제조 및 기계적 특성

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초　록　Vacuum Hot Pressing을 이용하여 제조한 TiNi형상기억섬유 강화 6061 Al기지 복합재료를 제조하고 미세조직 및 기계적 특성 등을 연구하였다. 제조된 복합재의 항복응력은 예비변형량, 섬유체적율 및 열처리에 따라 증가하였다. 복합재의 지적특성은 예비변형이 가하여진 후 재가열되었을 때 기지 내 TiNi섬유의 형상기억효과에 의한 압축잔류응력 발생에 기인된다. 미세조직 관찰 결과 섬유와 기지 사이에는 Al_3Ti 및 Al_3Ni의 금속간화합물층이 관찰되었다. 또한 시험온도 증가와 더불어 TiNi섬유강화된 복합재의 유동강도는 높은 값을 나타내었다.

Abstract 6061 Al-matrix composite with TiNi shape memory fiber as reinforcement has been fabricated by vacuum hot pressing to investigate the microstructure and mechanical properties. The yield stress of this composite increases with increasing amount of prestrain, and it also depends on the volume fraction of fiber and heat treatment. The smartness of the composite is given due to the shape memory effect of the TiNi fiber which generates compressive residual stresses in the matrix material when heated after being prestrained. Microstructural observations have revealed that interfacial reactions occur between the matrix and fiber, creating two intermetallic layers. The flow strength of the composite at elevated temperatures is significantly higher than that of the matrix alloy without TiNi fiber.

1. Introduction

The characteristics of shape memory alloys(SMAs) are associated with martensitic and its reverse transformations. A martensitic transformation in a SMA is induced not only by changing temperature but also by applying stress[1~5]. The martensite transformation temperature depends on the chemical composition of alloy, method of fabrication and heat treatment[6,7]. After being prestrained at temperatures below martensite finish temperature, Mf, following shape memorization, SMA fiber can shrink back to its original length when heated to and above its austenite finish temperature, Af. If such shrinkable SMA fiber is embedded in metals and alloys to form metal-matrix composite(MMC), compressive residual stress is induced in the matrix when heated up at least to austenite start temperature, As. This results in enhanced tensile flow stress of MMC. The concept of such a smart composite with TiNi fiber is shown in Fig. 1[1], which is described as follows. TiNi fiber is first heat treated to shape memorize their initial length at above Af temperature. It is then quenched to room temperature(around Ms in the present case), given prestrain and then embedded in the matrix to form a composite by, for instance, vacuum hot pressing. Composite thus produced is then heated to temperatures higher than Af where the TiNi fiber tends to shrink back to its initial length(i.e., shape recovery). The recovered strain is as much as the amount of prestrain if the constraint of the matrix material does not prohibit the shape recovery of the fiber. This shape recovery induces residual tensile stress in the TiNi

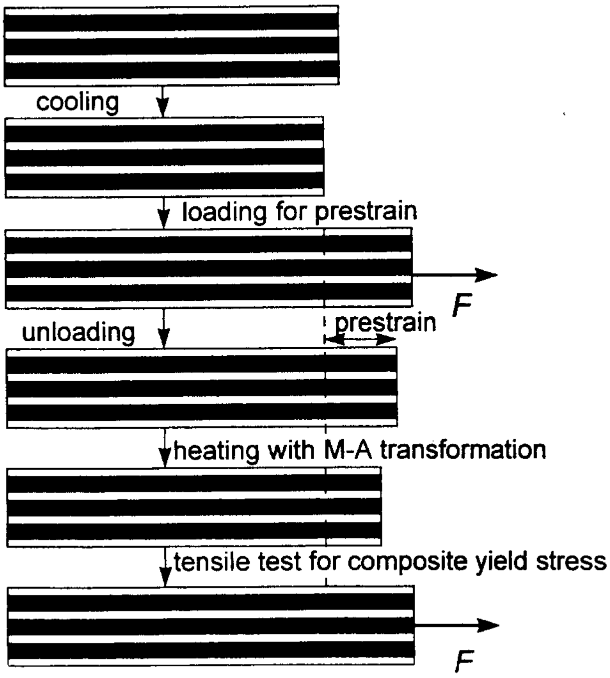

Fig. 1. Concept of Smart Composite with TiNi Fibers

fiber, while the matrix is subjected to compressive stress. This compressive stress generated in the matrix contributes to the enhancement of the tensile properties of the composite. The purposes of this work are to study the microstructure formed upon the fabrication of the 6061 Al-matrix composite containing TiNi fiber and to study effects of prestraining and volume fraction of fiber on the strength of the composite with and without aging heat treatment.

2. Experiment

TiNi fiber(Ti-50.3 at.% Ni) of 200㎛ diameter(made by Kantoc Ltd., Fujisawa, Japan) and sheet metal of 6061 Al alloy(0.5mm thick, Alcoa made) were used in this study to produce smart composite. The sheet metal was sheared off using a shear cutter into a rectangular shape of 10mm width and then slits of 0.3mm width and 1mm length were made in both narrow sides with an interval of 1mm using a low-speed diamond wheel cutter. After removal of oxide layer, TiNi fiber was wound around such 6061 Al alloy sheets through slits, and several prepreg sheets thus made were stacked on a pair of hot press dies. Then, composite specimens were fabricated by a custom-made vacuum hot press system at selected holding temperatures and pressures. After holding specimens under a set of holding pressure and temperature for a various period of time, composite specimens were cooled down to room temperature within a furnace. Two volume fractions were chosen in the study and they were 2.7 and 5.3%. Fig. 2 is a schematic illustration showing the hot pressing procedure of wire wound prepreg employed in the present study.

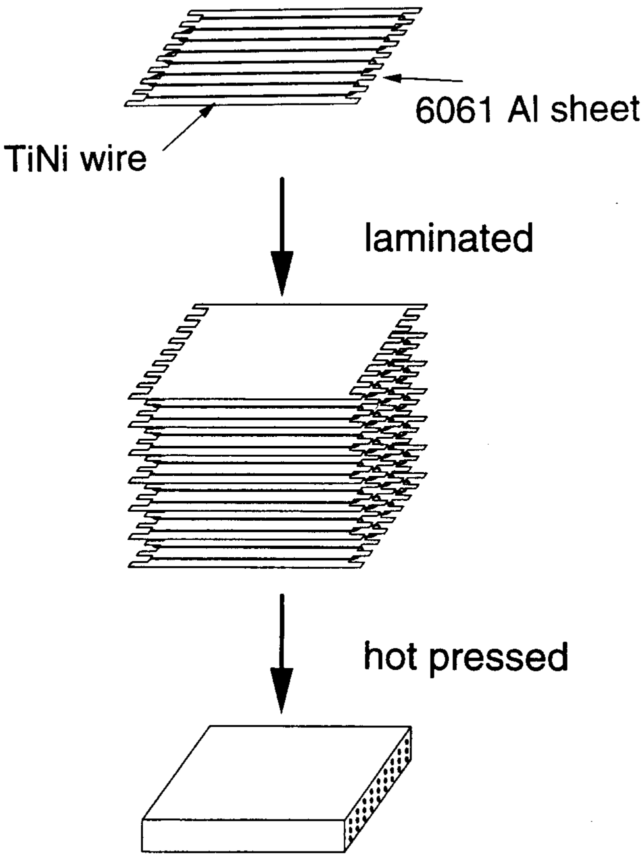

Fig. 2. Hot Pressing Procedure of Wire Wound Prepreg

Composite specimens were cut to produce tensile specimens, whose dimensions are 10mm wide and 90mm long with a gauge length of 26mm. To obtain mechanical properties and transformation temperatures of TiNi fiber used, tensile tests were performed at temperatures between 297 and 373K after shape memorizing treatment at 773K for 30min. in air followed by quenching into water. The transformation starting and finishing stresses can be obtained from tensile stress-strain curves obtained each test temperature. Differential Scanning Calorimeter(DSC) was also utilized for the measurement of transformation temperatures without stressing. In order to see the effects of T6 aging treatment on mechanical properties of the composite, the heat treatment was performed by following a standard procedure of 6061 Al alloy. That is, the solution treatment was first made at 803K for 1hr and then water quenched followed by the second heat treatment at 443K for 6hr and quenching. To investigate prestrain effects, various amounts of prestrain were given to some composite specimens by deforming them in ten-

Table 1. Transformation temperatures and elastic moduli of Ti-50.3 at% Ni SMA fiber and 6061 Al alloy.

	Ms	Mf	As	Af	Elastic Modulus
TiNi	288 K	280 K	318 K	329 K	26.3 GPa (Martensite) 67.0 GPa (Austenite)
6061 Al					70.0 GPa

sion at 293K. Tensile tests were performed on an Instron testing machine at a constant strain rate, 1 × 10^{-4}/s. The displacement of tensile specimens used in the study was measured by using an extensometer.

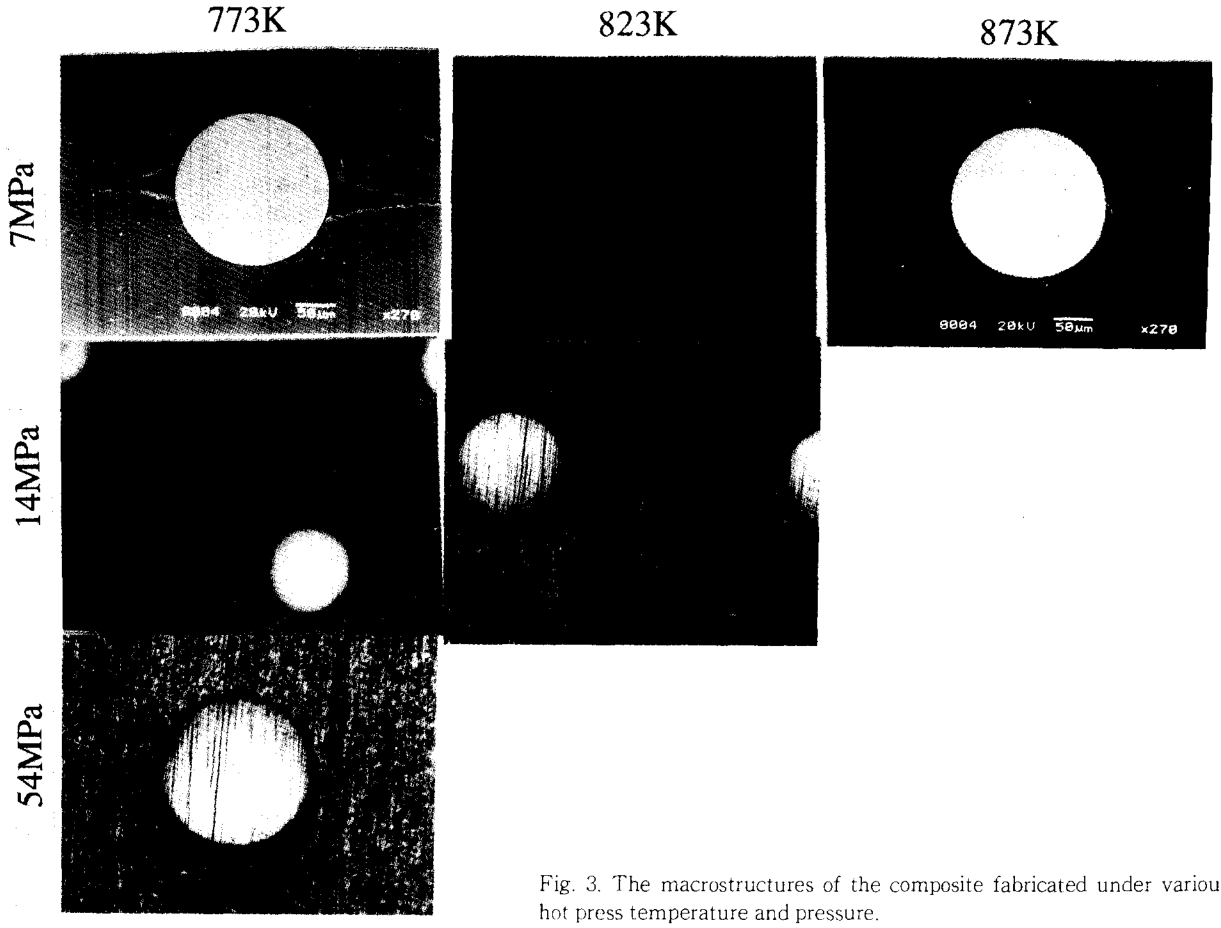

Fig. 3. The macrostructures of the composite fabricated under various hot press temperature and pressure.

3. Results

Processing and Microstructures

The transformation temperatures of TiNi fiber used in the present study were measured by a DSC, which are tabulated in Table 1. This table also contains the elastic moduli of the fiber for both martensite and austenite phases, which were measured from data obtained in tension tests using an extensometer. The table also contains the elastic modulus of 6061 Al alloy.

Fig. 3 shows the macrostructure of the composite fabricated under various hot pressing conditions. In the Fig TiNi fiber is seen as white circles in the 6061 Al matrix material. Maximum holding temperatures employed for vacuum hot pressing were 773, 803, 823, and 873K, and holding pressures chosen were 7, 14 and 54MPa. In all cases, the holding time was set to be 30min. at maximum temperatures. As seen in the Fig. 3, strong bonding between the matrix and the fiber may not be formed when the composite was fabricated at 7 and 14MPa at 773K and 7MPa at 823K. Good interface appears to be formed when fabricated at 7MPa at 873K, 14MPa at 823K and 54MPa at 773K. Fig. 4 shows the EPMA results of a 6061 Al composite sample contain-

Table 2. EPMA results obtained from regions in composite(at%).

Region	Al	Si	Cr	Cu	Ni	Ti
1					51.22	48.78
2	64.65	4.20			6.05	25.11
3	75.46				23.18	1.36
4	98.45		0.15	0.47	0.21	0.72

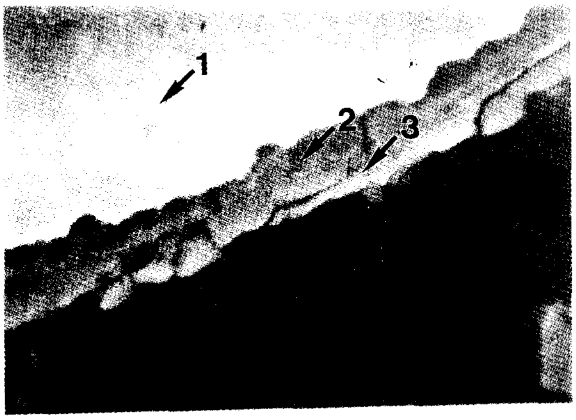

Fig. 4. EPMA semi-quantitative analysis of boundary reaction layer.

ing TiNi SMA fiber fabricated at a vacuum hot pressing of 7MPa at 823K for 30min. The elements of regions in the composite obtained by EPMA are tabulated in Table 2.

EPMA analysis revealed that there was a considerable interfacial reaction between the fiber and the matrix under this fabrication condition. As seen in region 1 of Fig. 4, only TiNi is seen. On the other side, in region 2, Al_3Ti was formed and Al_3Ni in the region 3. Such dual phase structures in interfacial regions has also been observed in Ti-matrix composite containing TiPd SMA fiber[8]. Fig. 5 shows typical SEM micrographs of the composite made by vacuum hot pressing at 773, 823 and 873K. It should be noted that the Al_3Ti phase is the only intermetallic phase formed in reaction areas when the composite was made at 773K. On the other hand, both Al_3Ti and Al_3Ni were formed both at 823 and 873K. At this moment it is not sure which interfacial structure has the strongest bonding.

Mechanical behavior

Fig. 6 shows yield stress-prestrain curves obtained in tension at 375K for the composite fabricated at 773K for 30min. followed by T6 aging treatment. This Fig also contains data for the composite without T6 aging treatment. In Fig. 6, prestrain was given at 293K. From this Fig, the yield stress is found to increase with increasing both the amount of prestrain and the volume fraction. It should be noted that T6 treated samples all show higher yield stress than that without T6 treatment. As seen, the yield stress after T6 treatment becomes about three times as high as that without T6 treatment. Another feature to be pointed is that the yield stress obtained by testing at 373K is also higher than that tested at 293K in Fig. 8. This stress increase is associated with the annihilation of stress-induced martensite formed upon prestraining. The following typical equations can be obtained by a least square fit method for the composite having a 2.7% volume frac-

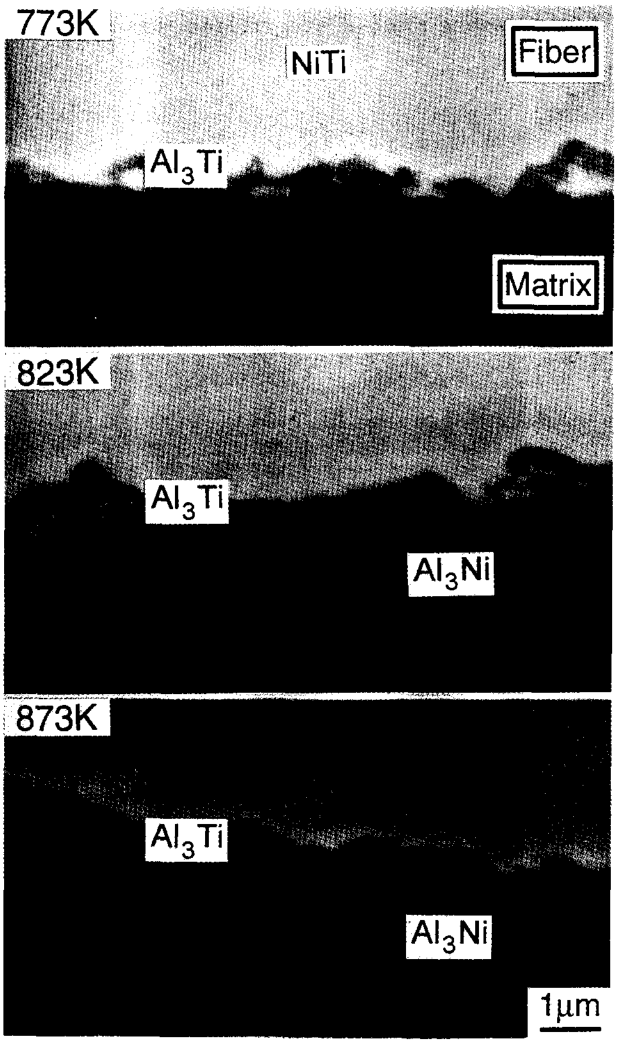

Fig. 5. SEM Micrographs of smart composite by hot pressing temperatures.

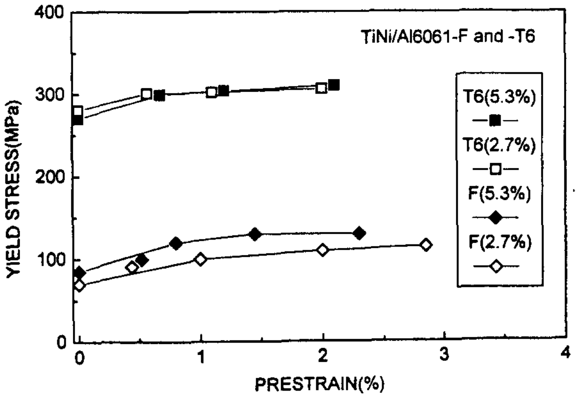

Fig. 6. Yield Stress vs. Prestrain Curves Testd at 375K.

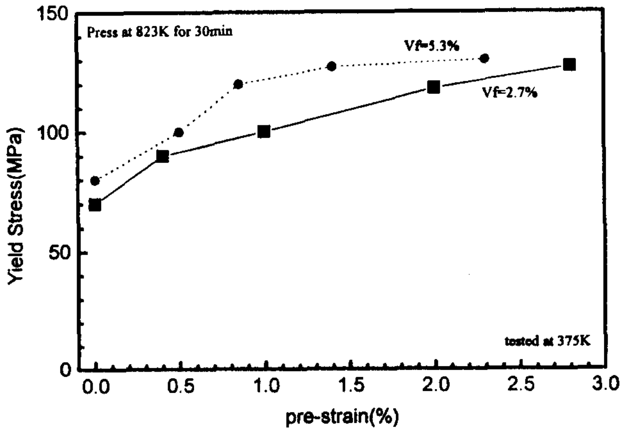

Fig. 7. Dependence of composite yield stress on pre-strain.

tion with and without T6 aging treatment.

Y = 15.677X + 283 with T6.

Y = 18.719X + 77 without T6.

where X is the amount of prestrain and Y is the yield stress.

Fig. 7 shows the prestrain dependence on yield stress for the TiNi/6061Al-F composite(where F stands for no heat treatment). The hot press condition used was at 823K for 30 min, and composite specimens made under this condition were tested at 375K. The results obtained from these specimens are very similar to those seen in Fig. 6. Fig. 8 shows the prestrain dependence on yield stress for TiNi/Al 6061-F composite specimens fabricated by vacuum hot pressing at 873K for 30min. This Fig show that the yield stress is higher when tested at higher temperature. The Fig also show that the yield stress is higher for higher prestrain. It is also shown that the composite becomes stronger when made at higher hot pressure. From the experimental results obtained, the optimum vacuum hot press conditions are considered to be a holding temperature of 773K, a holding time of 30min and a maximum pressure of 54MPa.

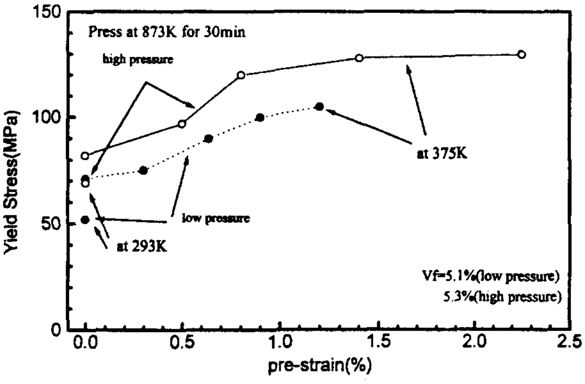

Fig. 8. Dependence of composite yield stress on pre-strain.

4. Conclusions

6061 Al-matrix composite containing TiNi SMA fiber was fabricated by vacuum hot pressing under various conditions, and the microstructure and mechanical properties have been investigated. The results obtained are summarized as follows.

1) The prestrain effects were clearly shown for the composite with and without aging treatment of 6061 Al alloy matrix composite containing TiNi SMA fiber.

2) The composite with TiNi SMA fiber used as reinforcement becomes stronger at high temperatures due to the generation of residual stress caused by a shape memory effect of TiNi fiber at above As or/and Af.

3) The yield stress of the composite increases with increasing prestrain, fiber volume fraction and test temperature at temperatures above the Af temperature.

4) To improve mechanical properties in this composite, T6 aging treatment is needed.

5) Interfacial reactions occur between TiNi fiber and 6061 Al matrix upon hot pressing at conditions employed, and the interfacial phases are intermetallics of Al_3Ti and Al_3Ni.

Acknowledgments

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References

1. M. Taya, A. Shimamoto and Y. Furuya, Proc. ICCM-10, Whistler, B.C., Canada,1995, p. V275-

V282.

2. K. Inoue, K. Hamada, J.H. Lee and M. Taya, Proc. TMS, Cincinnati, OH, 1996.
3. C. Lexcellent, H. Tobushi, A. Ziolkowski and K. Tanaka, Int. J. Pres. Ves. and Piping **58**, p. 51 (1994).
4. P.H. Lin, H. Tobushi, K. Tanaka, T. Hattori and M. Makita, J. Intell. Sys. and Str. **5**, p. 694 (1994).
5. W.D. Armstrong, J. Intell. Sys. and Str. **7**, p. 448 (1996).
6. J.H. Lee, J.B. Park, G.F. Andreasen and R. S. Lakes, J. Biom. Mater. Res. 22, p. 573 (1988).
7. Shape memory materials and phenomena - Fundamental aspects and applications, edited by C.T. Liu, H. Kunsmann, K. Otsuka and M. Wuttig (Mater. Res. Soc. Proc. 246, Boston, MA 1991), p. 13-55.
8. T. Hoshiya, K. Inoue and K. Enami, TMS p. 99-106 (1995).