MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AL MATRIX COMPOSITES PRODUCED BY LCCS PROCESS

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SUMMARY: Three kinds of metal matrix composites(MMCs) were produced in situ by Low Pressure Casting/Combustion Synthesis(LCCS) Process. Near-net-shape trialuminide-reinforced composites can be fabricated without cavities. The reaction between Nb powder and molten Aluminum was negligible at the present processing condition. Mechanical properties of Al-matrix composites reinforced by Al_3Fe were poor because of the heterogeneous dispersion of reinforcement by coarse Al_3Fe. In all composites investigated, good mechanical properties were obtained from Al-matrix composite containing Al_3Ti. In this case, it was indicated that wetability between matrix and reinforcement was good. With increasing Al_3Ti in MMC, the tensile strength of Al/Al_3Ti composites was improved at the expense of their ductility.

Keywords: low pressure casting, vacuum suction, combustion synthesis, metal matrix composite, aluminum, Al_3Ti, intermetallic compound

INTRODUCTION

Out of metal matrix composites (MMCs), Aluminum-aluminide composites offer unique features including a combination of different properties given by the constituent phases. They are, for instance, high stiffness and strength of an aluminide and high elongation and low density of aluminum. Such composites are attractive to many industries in various applications. Industries include automotive or aircraft manufacturers, in which generally cost reduction while supplying better products is a significant factor in selecting innovative process methods [1,2]. Methods for fabricating composites having one brittle component include high-pressure casting, diffusion bonding and, sputter or vapor deposition techniques [3-5]. These techniques either require high processing temperatures and pressures or are time intensive. Besides, they also require sophisticated manufacturing equipment. All of these are the factors to strongly related to production costs of such composites. Hence those fabrication methods become less attractive in practical manners.

Thus, it is significant to develop new fabrication methods for making MMCs economically. Combustion synthesis, also termed high-temperature synthesis (SHS), is believed to be an economical and environmentally benign technique and can possibly be used to form MMCs through solid-solid reactions between elemental constituents [6-8]. From the above-mentioned viewpoint, we recently developed an innovative processing technique to fabricate near-net-shaped aluminum-matrix composites reinforced by aluminides [9-11]. The technique is involved in both low pressure casting [12-14] and combustion synthesis, and it was named a LCCS process [9].

In the present study, three kinds of aluminide-reinforced Al matrix composites have directly been fabricated from Al-based powder mixtures and molten Al. Micro and crystal structural observations of the composites fabricated by the process have been performed by means of scanning electron microscopy and X-ray diffraction.

EXPERIMENTAL PROCEDURE

In a previous study [9], fabrication process of aluminide-reinforced Al-matrix composites has been shown. The process is described here in brief. In the process, 304 stainless steel pipe was used as a metallic mold to fabricate rod-shaped composites, see Figure 1. Commercially available 99.98% purity Al powder, 99% purity Ti powder, 99.9% purity Nb powder and 99.98% purity Fe powder were used as raw materials and their average diameters are respectively 86.2, 82.6, 83.5 and 110.7 m. The particle size distribution of these powders is shown in Table 1. From these elemental powders, three kinds of powder mixtures were prepared and they are Al-30at%Ti, Al-30at%Nb and Al-30at%Fe.

Table 1: Particle size distribution of as-received Al, Ti, Nb and Fe powders.

Particle diameter(m)	180-150	150-125	125-106	106-90	90-75	75-63	63-53	53-45	45-25	25-
Al(%)	-	0.8	7.3	23.8	38.3	24.3	4.5	0.8	0.2	-
Ti(%)	-	1.4	14.1	22.5	28.4	17.9	6.1	5.6	4.0	-
Nb(%)	-	0.1	3.8	29.0	33.3	21.2	8.8	2.8	1.0	-
Fe(%)	0.6	15.0	27.6	21.0	15.5	10.0	5.2	2.4	2.1	0.6

A pipe with a central part 10mm long is first compressed to 2.5mm thick. Then, a small amount of Al_2O_3-SiO_2 ceramic fiber is inserted into the pipe from its one end and softly packed in order to close the compressed narrow channel, as shown in Figure 1. Then, the powder mixture is tapped after insertion into a stainless steel pipe from the same end of the pipe where the ceramic fiber has already been packed. The relative packing density achieved by tapping is around 50%. The open end of the pipe containing the powder mixture is capped with plastic film 3 m thick and 12mm in diameter, and the other end is connected to a vacuum pump. While the pipe is being pumped for degassing, the pipe is inserted into molten Al from the pipe end covered with plastic film. This film is burn out immediately when molten Al is in contact and then combustion synthesis reaction occurs when Ti, Nb or Fe powders are in direct contact with molten Al, resulting in the formation of aluminides near the pipe end. Aluminides formed in this stage are porous and thus molten Al infiltrates into the pipe through cavities in skeletons of aluminides. Molten Al thus contacts non- or partly-reacted powder around aluminides. Through this process, the porous aluminides form at the end first and then move to the pressed center portion of the pipe. Simultaneously, molten Al moves from the pipe end toward the pipe center, and cavities are filled in the aluminide skeleton. After such a reaction is terminated, the pipe is cooled and residual molten Al in the pipe solidifies, resulting in the formation of aluminide-reinforced Al matrix composites.

In the present study, the temperature of molten Al has been kept to be at around 1193K. Composites produced were examined by SEM, X-ray diffraction and EPMA

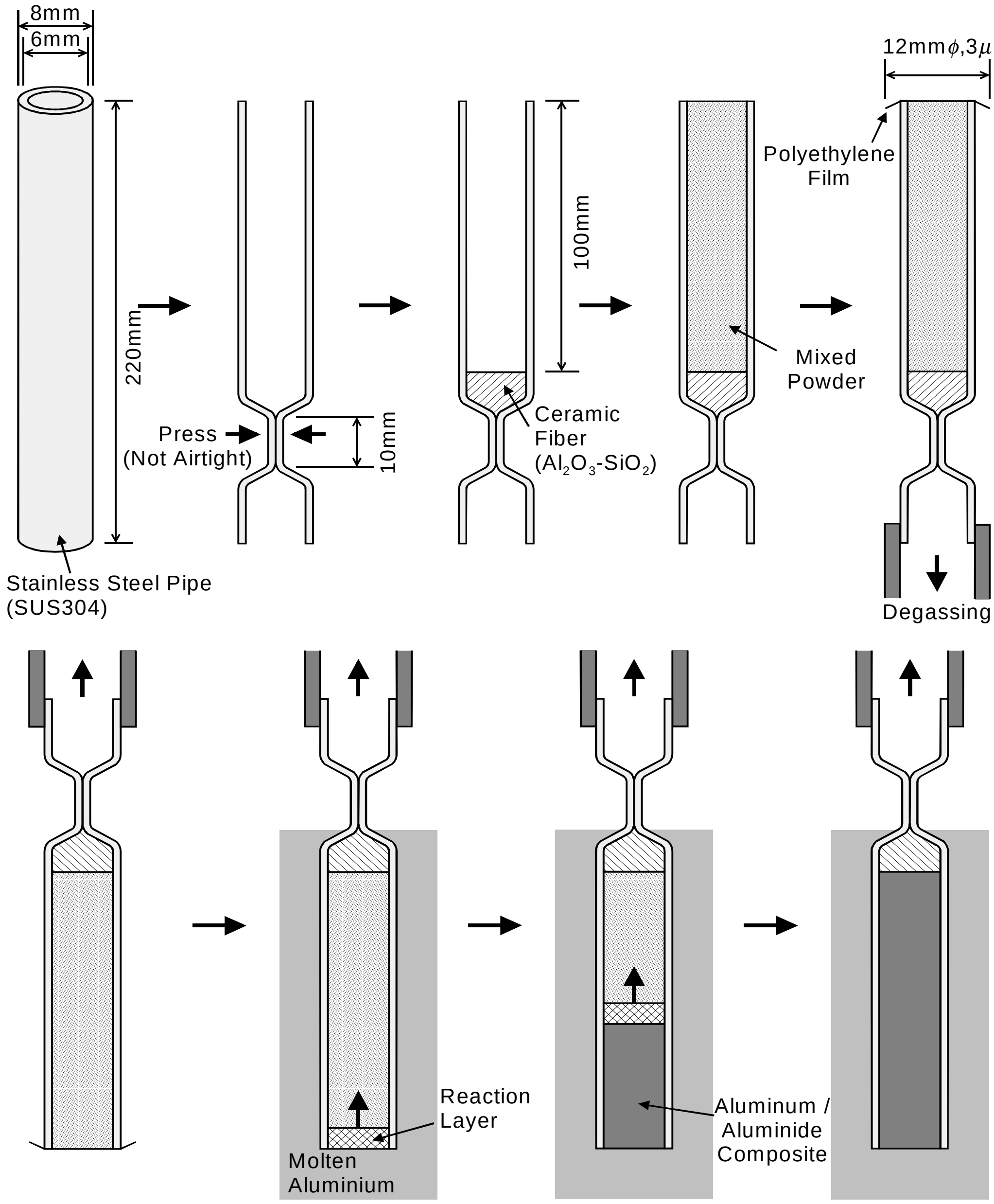


Figure 1: Low-pressure casting/combustion synthesis (LCCS) process.

techniques. A JOEL 5800LVC scanning electron microscope and Mac Science MXP-18 X-ray diffraction apparatus were used. Mechanical properties were examined at room temperature using a Vickers hardness tester at a load of 98.1N and Instron testing machine.

RESULTS AND DISCUSSION

Microstructure and Phases Present

Three kinds of the composites fabricated in the present study were examined by X-ray diffraction for identification of phases. X-ray diffraction patterns taken from composites A, B and C are shown in Figure 2. Each composite consists of three kinds of phases. All the phases present in the composites can be identified as Ti, Al and Al_3Ti in composite A, as Nb, Al and Al_3Nb in composite B and as Fe, Al and Al_3Fe in composite C. Scanning electron micrographs taken from composites A, B and C are shown in Figure 3. In the case of the

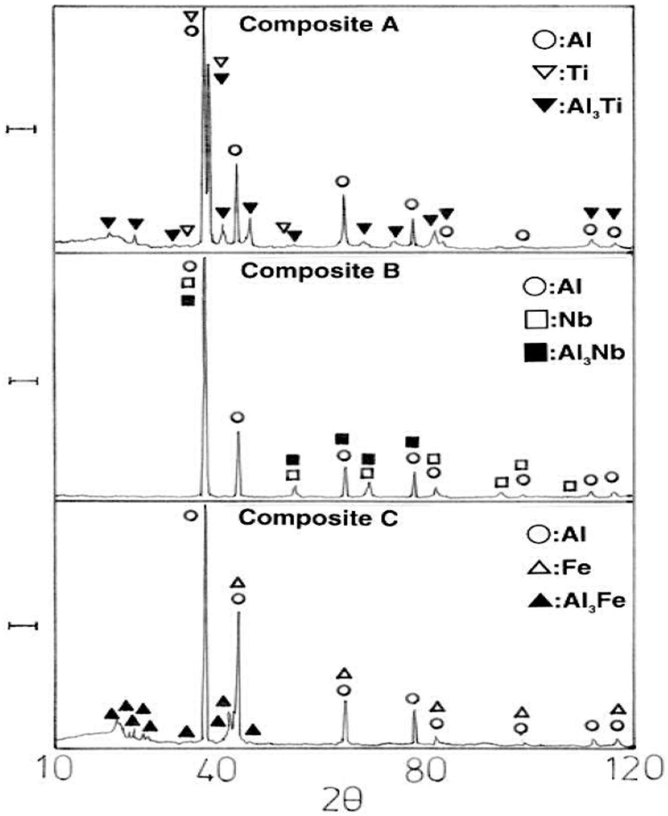
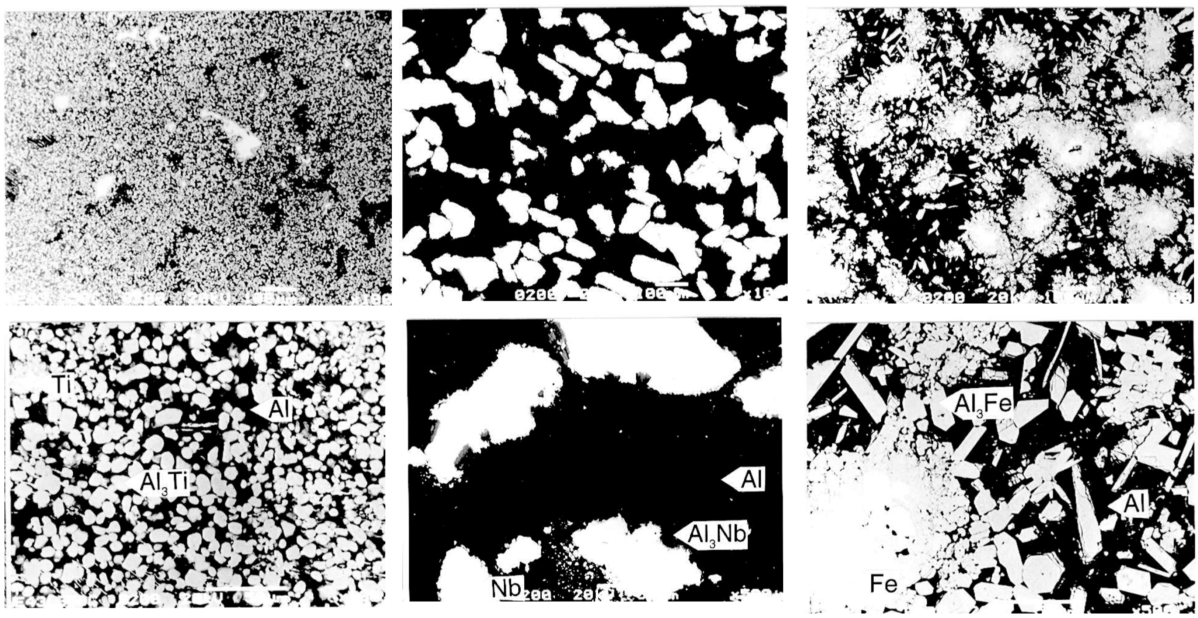


Figure 2: X-ray diffraction profiles taken from Al-matrix composites fabricated by the LCCS process. Composite A: Al-30at.%Ti; composite B: Al-30at.%Nb; and composite C: Al-30at.%Fe.

composite B, only the outer rim of Nb particles transformed to Al_3Nb with an inner core of Nb that remained non-reacted. To promote a further reaction between Nb and molten Al, processing conditions may be needed to modify. Such conditions would be, for example, duration time of pipe insertion or increase in temperature of molten Al. By contrast, microstructures of composites A and C reveal complete reactions of essentially all elemental powders to form aluminides.

It should be noted that there are some microstructural differences between composites A and C. In the case of composite A, the microstructure is homogeneous and fine spherical particles of Al_3Ti are dispersed with a mean diameter of about 8 m In the case of composite C, on the other hand, Al_3Fe reinforcements are formed in the shape of coarse flakes and heterogeneous dispersion of Al_3Fe was observed. These



Composite A Composite B Composite C

Figure 3: Scanning electron micrographs taken from three Al-matrix composites fabricated by the LCCS process.

microstructural differences could be caused by the following two reasons. One is that heat formation of Al_3Ti (35.0kcal/mol) is much larger than that of Al_3Fe (18.9kcal/mol), and the other is that the crystal structure of Al_3Ti is tetragonal, whereas it is monoclinic for Al_3Fe.

Mechanical Properties

Vickers hardness measurements were performed for composites produced by the present LCCS process and results obtained are summarized in Figure 4. As seen, the hardness value of composite B was much lower than that of composites A and C. This low hardness value of composite C would be related to a small amount of Al_3Nb particles formed upon reaction. All composites fabricated in the present study were machined to make tensile specimens with gauge dimensions of approximately 5mm in diameter and 10mm long and tests were carried out at room temperature at a strain rate of $1x10^{-4}$. Results obtained are shown in Figure 5. From this figure, it is seen that the tensile strength and elongation of composite A were much higher than those of composites B and C. That is, the tensile strength reaches higher than 300MPa, and the elongation is about 4%. These results are caused by the presence of homogeneously distributed fine dispersion of Al_3Ti. By contrast, the tensile strength of composites B and C were quite low and less than 100MPa, and their elongation was about 0.1%. These poor mechanical properties of composite B are caused by scant reaction of Nb powder with molten Al during processing. In the case of composite C, a heterogeneous dispersion of coarse Al_3Fe particles could be attributable to brittleness

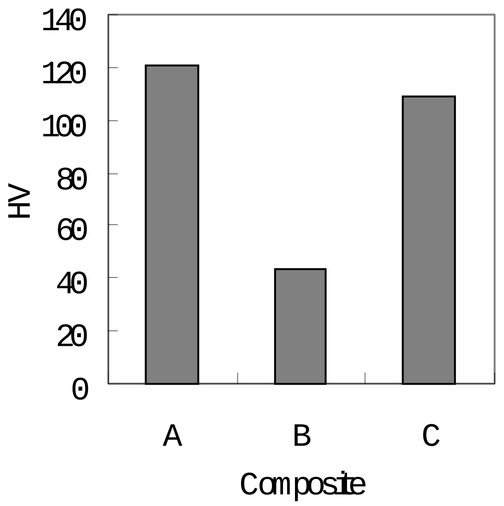


Figure 4: Vickers hardness (at a load of 10kg) of Al-matrix composites.

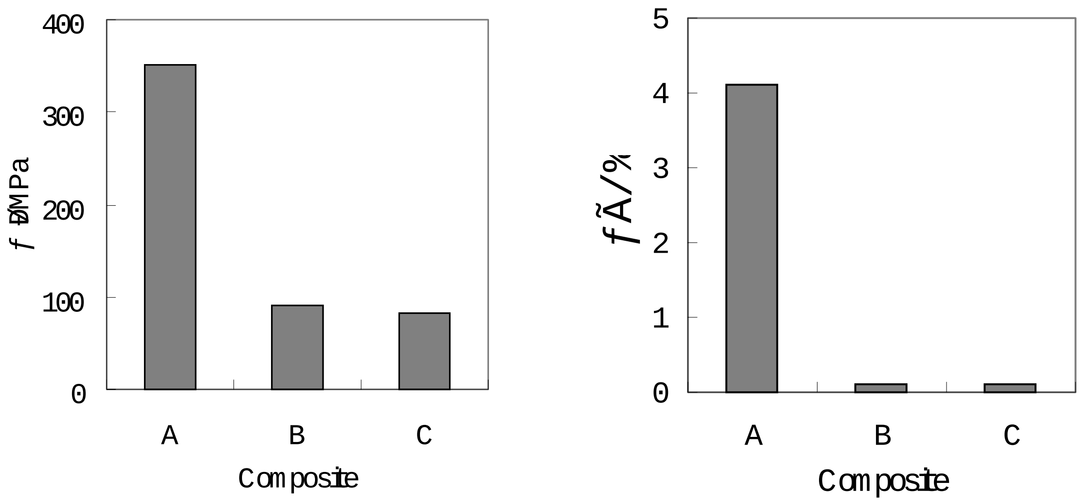


Figure 5: Tensile strength and elongation of Al-matrix composites.

of the composite, although the reaction of Fe with molten Al appeared completed.

Fracture Behavior

Scanning electron micrographs of fractured specimens are shown in Figure 6. These results agreed qualitatively with the tensile test results. In composite A where fine Al_3Ti particles were formed uniformly, typical ductile dimples appear on the fracture surface, see Figure 6(a). Figure 6(b) is a higher magnification micrograph of Figure 6(a), showing also transgranular cracks of Al_3Ti particles. This result suggests that Al-matrix composite with Al_3Ti particles has good bonding between the matrix and the particles. Thus, the failure can be described as follows. Cracking first occurs in brittle Al_3Ti particles; then, as load is further increased, Al matrix undergoes formation and coalescence of microvoids, leading to a ductile rupture of the composite.

On the other hand, composites B and C fractured in brittle manners. In composite B, as shown in Figure 6(c), de-bonding occurred between Nb particle and Al matrix. This indicates week bonding between Nb particle and Al matrix. Figure 6(d) shows the fracture surface of composite C, showing a typical brittle fracture mode of composite C. In this case, although the ductile Al matrix was present, it appears the matrix did not make bridges to connect several cracks that were formed in Al_3Fe particles during deformation. This fracture manner may be caused by the heterogeneous precipitation of coarse Al_3Fe particles. From these fracture surface observations, it was found that Al-matrix composites containing Al_3Ti

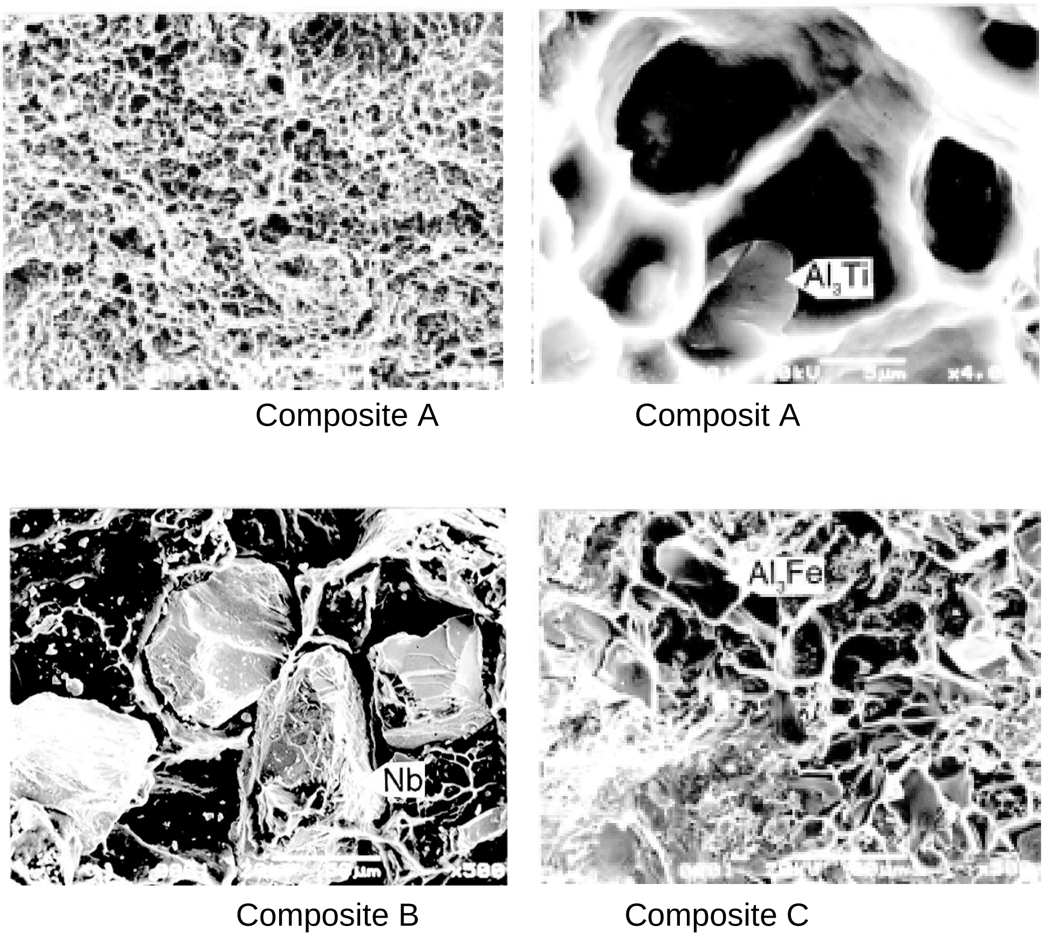


Figure 6: Fracture surface of Al-matrix composites fabricated by the LCCS process.

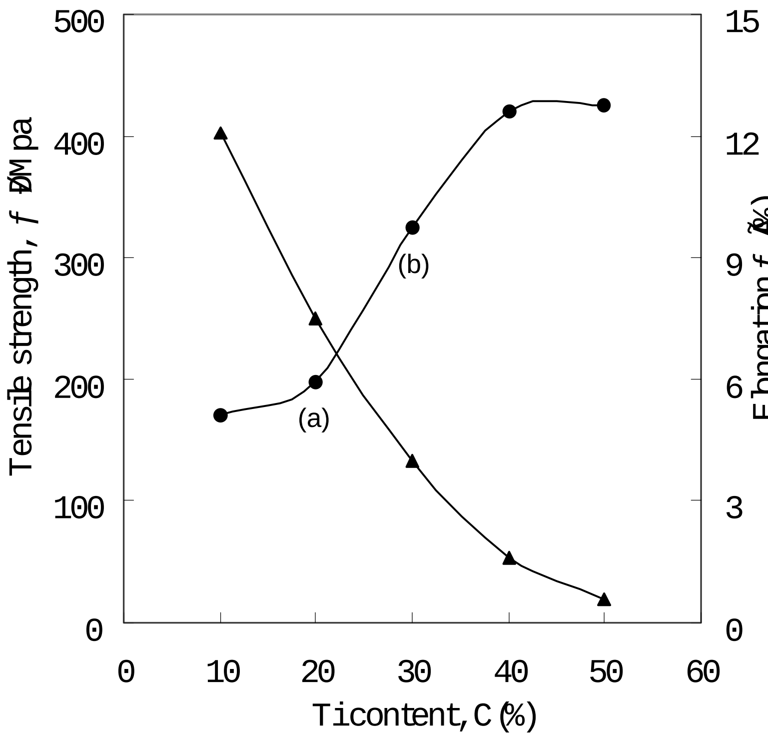
particles showed the best mechanical properties among these three kinds of the composites fabricated in the present study.

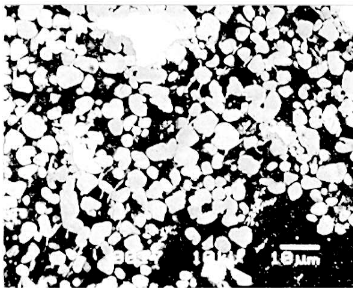
Al/Al_3Ti Composite: Effect of Ti Content

In order to investigate the effect of processing parameters for the mechanical properties of Al-matrix composites reinforced by Al_3Ti particles, further tensile tests were performed. Figure 7 shows microstructures and their corresponding mechanical properties for Al_3Ti-containing Al-matrix composites as a function of Ti content. As seen, the tensile strength becomes higher with increasing Ti content in powder mixtures. When Ti content is 40 or 50vol. %, tensile strength reaches as high as 400MPa. On the other hand, the elongation of the composites decreases with increasing Ti content. These mechanical properties and microstructures indicate that ductility of the composites can be changed by Ti content through modifying the volume fraction of Al_3Ti in the composites. It is evident that as the volume fraction of Al_3Ti increases, the tensile strength of the composite becomes larger at the expense of ductility. It should be pointed out that Al-matrix composites containing Al_3Ti show high strength and relatively high ductility when Ti content is around 30%. It is known that ductility can be improved by modification of the crystal structure in the case of Al_3Ti from DO_{22} to $L1_2$ by ternary additions [15-17], and thus similar techniques may be used to improve ductility in the present case without losing strength appreciably.

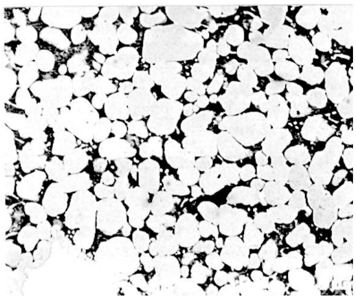
CONCLUSIONS

(c)



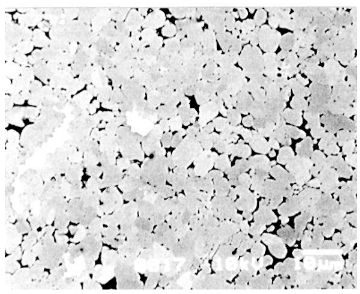


(a)



(b)

Three kinds of



(c)

Figure 7: Microstructures and mechanical properties of Al-matrix composite containing Al_3Ti as a function of Ti content.

metal matrix composites containing tri-aluminides, Al_3Ti, Al_3Nb and Al_3Fe, were fabricated in situ by Low Pressure Casting/Combustion Synthesis (LCCS) Process from three kinds of powder mixtures. Prepared powder mixtures were Al-30at%Ti, Al-30at%Nb and Al-30at%Fe. Near-net-shape aluminide-reinforced composites could be fabricated without cavities by LCCS and the microstructure and mechanical properties of the composites were investigated. In the case of Al-Nb powder mixture, a combustion synthesis reaction occurred negligibly at the surface of Nb particles. On the other hand, in the case of Al-Ti and Al-Fe powder mixtures, almost all Ti and Fe powders were consumed during LCCS and formed Al_3Ti and Al_3Fe as composite reinforcements, respectively. In the case of the Al-matrix composite containing Al_3Fe, tensile strength and ductility were low because of heterogeneous dispersion of coarse Al_3Fe particles. In all composites fabricated, Al/Al_3Ti composite revealed the highest tensile strength and elongation. This is caused by the homogeneous dispersion of fine Al_3Ti particles. With increasing the volume fraction of Al_3Ti in MMC, the tensile strength was increased significantly at the expense of ductility.

REFERENCES

[1] Y. Nishizawa, T. Miyashita, S. Isobe and T. Noda, «Development of Titanium Aluminide Turbocharger Rotors», *High temperature Aluminides and Intermetallics*, eds. S. H. Wang, C. T. Liu, D. P. Pope and J. O. Stiegler,(Warrendale, PA: The Metallurgical Society, (1990), pp. 557-584.

[2] M. C. Flemings, «Materials Futurethink», *Advanced materials and Processes*, Vol. 145 (1), (1994), pp. 22-24

[3] D. E. Alman et al., «Processing, Structure and Properties of MoSi2-Base Composites«, *Mater. Sci. Engr*., A155, (1992), pp. 85-93.

[4] R. G. Rowe and D. W. Kelly, «The Synthesis and Evalation of Nb_3Al/Nb Laminated Composites», *Intermetallic Matrix Composites* , eds. D. B. Miracle, D. L. Anton and J. A. Graves, (Pittsburgh, PA: MRS, 1992), pp. 411-416.

[5] D. A. Hardwick and R. C. Cordi, «Intermetallic Matrix Composites by Physical Vapor Deposition », *Intermetallic Matrix Composites*, eds. D. L. Anton et al.(Pittsburgh, PA, MRS, 1992), pp. 65-70

[6] D. E. Alman and N. S. Stoloff, «Powder Fabrication of Monolithic and Composite NiAl», *Intl. J. Powder Metallurgy*, Vol. 27, (1991), pp. 29-41.

[7] D. E. Alman and N. S. Stoloff, «Preparation of $MoSi_2$/SiC Composites from Elemental Powders by Reactive Co-Synthesis», *Scripta Metallugia et Materialia*, Vol. 28(1993), 1525-1530.

[8] D. E. Alman, J. A. Hawk and M. Ziomek-Moroz, «Properties of in-situ TiAl- and MoSi2-base Composites Produced by Reactive Processing», *In situ Reactions for Synthesis of Composites, Ceramics and Intermetallics*, eds. E. V. Barrera, S. G. Fishman, F. D. S. Marquis, N. N. Thandhani, W. E. Frazier and Z. A. Munir, The Minerals, Metals and Materials Society, (1994), pp. 141-157.

[9] K. Mizuuchi, T. Takeuchi, M. Fukusumi, M. Sugioka and H. Nagai, «Production of Al/Al_3Ti Composites by Low Pressure casting-Combustion Synthesis Process», *J. of*

The Japan Inst. of Metals, Vol.62, No.6, (1998), pp. 551-556.

[10] K. Mizuuchi, T. Takeuchi, M. Fukusumi, M. Sugioka and H. Nagai, «Effect of Processing Condition on the Properties of Al/Al_3Ti Composites Produced by LCCS Process», *J. of The Japan Inst. of Metals*, Vol. 62, No. 10, (1998), pp. 893-898.

[11] K. Mizuuchi, T. Takeuchi, M. Fukusumi, M. Sugioka, H. Nagai and K. Inoue, «Processing of Al/Al_3Ti Composites by Low Pressure Casting/Combustion Synthesis Process», *Proceedings of Third Pacific Rim International Conference on Advanced Materials and Processing(PRICM-3)*, Vol. I, (1998), pp. 497-503.

[12] K. Kubo, I. Ohnaka, T. Fukusako and K. Mizuuchi, «Measurement of Thermal Conductivity of Sand Molds by Parameter Optimization technique», *The journal of The Japan Foundrymen's Society*, Vol. 53, (1981), pp. 627-634.

[13] K. Kubo, I. Ohnaka, T. Fukusako and K. Mizuuchi, «Measurement of Thermal Properties of sand Molds by Pouring Method Using Steel», *The journal of The Japan Foundrymen's Society*, Vol. 55, (1983), pp. 362-368.

[14] K. Kubo, K.Mizuuchi, I. Ohnaka and T. Fukusako, «Measurement of Thermal Properties of Sand Molds by Pouring Method», *Proc. 50th Intl. Foundry Congress*, Vol. 6, (1983), pp. 1-12.

[15] H. R. P. Inoue, C. V. Cooper, L. H. Favrow, Y. Hamada and C. M. Wayman; *Mat. Rec. Soc. Symp. Proc.*, Vol. 213, (1991), pp. 493.

[16] H. R. P. Inoue, M. Kitamura, C. M. Wayman and H.Chen, *Philos. Mag. letters*, Vol. 63, (1991), pp. 345.

[17] K. Mizuuchi, Y. Okanda, M. Kitamura, C. V. Cooper, A. F. Giamei and H. R. P. Inoue, «Micro- and Crystal-Structural Observations of Al-rich Nb and Al-rich Ti Alloys», *Mat. Res. Soc. Symp. Proc.* Vol. 288, (1993), pp. 1191-1196.