HIGH STRAIN RATE SUPERPLASTICITY OF CERAMIC PARTICULATE REINFORCED ALUMINUM COMPOSITES AND THE FABRICATION PROCESSING

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SUMMARY: Metal matrix composites (MMC) fabricated by a vortex method, squeeze casting and PM method have already been applied to automobile engine components, satellite components and even for semi-conductor packings. It is important to clarify deformation mechanism involved in high strain rate superplasticity(HSRS) which exhibits a total elongation of 250~600% at strain rates of about 0.1~10s-1 and to establish a cost-effective fabrication processing for HSRS materials.

An AlN/1N90 PM pure aluminum composite were hot-rolled after extrusion.The deformation mechanism of the HSRS were investigated. A maximum tensile elongation of about 200% of the AlN/1N90 Al composite was obtained in a strain rate range of 0.1~0.3 s-1 and at 913K.

The results indicate that the optimum strain rate at which a maximum elongation is obtained is related to the fine grain size and that the primary deformation mechanism in HSRS is fine grain boundary sliding.

Effect of hot rolling condition on the superplastic characteristics of the SiCp/6061 Al alloy composite fabricated by a vortex method before squeeze casting and extrusion were examined. The composite was hot-rolled at 573K with a rolling strain per passes of 0.05~ 0.3 and exhibits a m value of 0.4~0.6 and a total elongation of 200~300% in the strain rate range of 0.08~1.3 s-1 at 853K. The optimum rolling temperature to produce a m value of more than 0.4 and a total elongation of 300% were 573, 673 and 723K.

TEM observations indicate that the SiC/6061 Al composite has a grain size of about 2µm with dispersed fine dispersoids after hot rolling. There was no major microstructure variation during the superplastic deformation.

KEYWORDS: superplasticity, SiC, 6061 aluminum, composite, a vortex method, hot rolling

INTRODUCTION

High strain rate superplasticity (HSRS) in ceramic whisker or particulate reinforced aluminum alloy composites is expected to offer an efficiently near-net shape forming technique to automobile, aerospace, and even semi-conductor industries, since the HSRS composites usually exhibit a total elongation of 250~600% at a high strain rate of about 0.1~10 s^{-1} [1-12] as shown in Table 1.

Metal matrix composites (MMC) fabricated by squeeze casting, a vortex method, compocasting, a powder metallurgical (P/M) method and spray deposition could produce HSRS. Among fabrication processing of MMC, casting processes such as squeeze casting, compocasting and a vortex method are cost effective so that composites fabricated by these processing methods have already been applied to automobile engine components, satellite components, and so on. A serious problem of cast aluminum alloy composites reinforced by relatively larger size ceramic particles is their low tensile ductility and fracture toughness at room temperature, since the composite just after being fabricated by a vortex method includes a lot of defects. Therefore, it is important to control fine microstructure for any aluminum alloy and ceramic system composites fabricated by casting processing and to produce the HSRS.

It has been pointed out that primary deformation mechanisms of the HSRS composites include grain boundary sliding, interfacial sliding at liquid phase and dynamic recrystalization because the decreasing of a grain size is related to the increasing of the optimum strain rate at which maximum total elongation of the HSRS composites is obtained and also the HSRS usually produces above or below solidus temperature of the matrix [1-12]. An interfacial sliding at liquid phase is expected to take an important role as accommodation mechanism to achieve larger elongation in the HSRS composites. It has not yet, however, made clear how interfacial sliding at liquid phase could promote the HSRS phenomena. It is necessary, therefore, to investigate effect of testing temperature on superplastic behavior of pure aluminum based composite to make clear deformation mechanism of HSRS.

The purpose of this study is to investigate effect of testing temperature on the HSRS in a AlN particulate reinforced 1N90 pure aluminum composites and to make clear the effect of hot rolling condition after extrusion and squeeze casting on HSRS behavior of a SiC particulate reinforced aluminum alloy composite fabricated by a vortex method. In addition, the deformation mechanism of the HSRS in the composite will also be discussed.

EXPERIMENTAL PROCEDURE

AlN particle (average particle size of 1.35µm) and α–SiC particles(the average particle size of 0.6µm, the chemical composition by weight%:94.0SiC, 1.3SiO_2, 1.53Si, 1.05C, 0.09Fe, 0.02Al) were used as reinforcement material. Table 2 indicates chemical composition of AlN particle and 1N90 pure aluminum powder. Chemical compositions of 6061 aluminum alloy used as matrix and of the SiC/6061 Al composite fabricated by a vortex method are shown in Table 3. AlN/1N90 Al composite was sintered with the pressure of 200 MPa under 773K for 20 minutes and extruded with the extrusion ratio of 44 at 773K.

Table :1 Superplastic characteristics of aluminum matrix composites

Fabrication Processing	Materials *1	Vf*2	Temp. (K)	Strain rate(1/s)	Elongation (%)	m value	Ref.
PM+Ex	SiCw/2124	0.20	798	0.3	300	0.3	1
	Si3N4w/2124	0.20	798	0.2	250	0.5	2
	Si3N4w/6061	0.20	818	0.2	600	0.5	3
	Si3N4w/7064	0.20	798	0.8	160	0.34	4
	Si3N4p/6061	0.20	818	0.1	600	0.5	5
PM+Ex +Roll	AlNp/6061	0.15	873	0.1~1.0	300~500	0.5	6
	SiCp/6061	0.175	853	0.1	375	0.5	7
	AlNp/1N90	0.15	913	0.1	200	0.3	8
	TiCp/2014	0.15	818	0.8	200~300	0.23	9
	TiCp/6061	0.15	873	0.8	200	0.3	9
	TiB2p/6061	0.15	873	0.1~0.8	200	0.26	10
	TiB2p/2014	0.15	818	0.1~0.8	200	0.25	10
SQ+Ex	Si3N4w/6061	0.25	818	0.07	170	0.3	11
	Si3N4w/2024	0.27	773	0.17	175	0.5	12
	SiCw/7075	0.27	773	0.1	---	0.3	13
	SiCw/6061	0.20	823	0.17	300	0.3	14
	SiCw/2324	0.20	793	0.05	520	0.47	15
Vor+Ex	SiCp/2024	0.20	515	0.0004	685	0.4	16
Vor+SQ+ Ex+Roll	SiCp/6061	0.20	853	0.2	200	0.3	17

Fabrication processing:SQ:Squeeze casting, Vor:Vortex method, Ex:Extrusion,
Roll:Rolling, PM:Powder metallurgy
*1:w:whikser, p:particle, *2:Vf:volume fraction of reinforcement

Table 2 Chemical composition of 1N90 pure aluminum and AlN particle

materials	Fe	Si	Cu	Mg	Ni	Ti	Mn	Zn	O	N	C	d50
1N90	ppm 43	ppm 41	ppm 6	ppm 3	ppm 3	ppm 2	ppm 5	ppm 17				45
AlN	ppm 50	ppm 100							wt% 1	wt% 33.8	wt% 0.2	1.35

AlN:a carbothermal nitridation **d_{50}(μm)**

Table 3 Chemical composition of 6061 Al matrix and SiC/6061 Al composite

Materials	Si	Cu	Fe	Zn	Mg	Mn	Cr	Ti
6061	**0.68**	**0.29**	**0.20**	**0.14**	**0.75**	**0.03**	**0.07**	**0.02**
SiC/6061	***8.67**	**0.25**	**0.40**	**0.16**	**0.90**	**0.02**	**0.06**	**0.16**

***:The Si content includes the value of SiC particle** **(wt%)**

Molten 6061 aluminum alloy heated at 1023K was stirred with the heated SiC particles and with 0.3wt%Ca and 0.15%Sb at a rotating speed of 500~700rpm in a crucible for 10.8Ksec. Also, 0.3wt%Mg was added to 6061 aluminum alloy of 40Kg to compensate for evaporation during stirring so that the final Mg content in the matrix became 0.90wt%. Ti was added as Al-5mass%Ti-B alloy. The volume fraction (Vf) of SiC particle was about 0.20. The as-cast composite was further forged at 1123K in air under an applied pressure of 100MPa by a squeeze casting machine in order to remove the defects.

Thermomechanical processing, including further hot rolling, was used to produce the HSRS composite. Hot rolling was carried out at 923K for AlN/1N90 Al PM composite. The hot extrusion for SiC/6061 Al composite was performed at 573 and 673K. Rolling strain per pass used 0.1 and the reheating time between each rolling pass was about 5 minutes. The final thickness of the hot-rolled composite was about 0.75mm (total strain was about 2.4). Tensile specimens with a 4mm gage width and a 5.5mm gage length were made. The AlN/1N90 Al composite were pulled at 873, 893 , 913, 923K and the SiC/6061 Al composite was pulled at 853K and at strain rates ranging from 1×10^{-3} to $2s^{-1}$. The microstructure and fracture surface of the sample were examined by TEM and SEM.

RESULTS AND DISCUSSION

Microstructure

Fig.1 shows SEM microstructures of the SiC/6061 Al composites just after hot rolling. SiC particles are dispersed homogeneously in the hot-rolled SiC/6061 Al composites, although a vortex method is so difficult processing as to make fine SiC particles of 0.6μm disperse homogeneously and reinforcement-free aluminum alloy layer is present. The fact that SiC particles are dispersed along grain boundaries probably restrains grain growth during hot rolling.

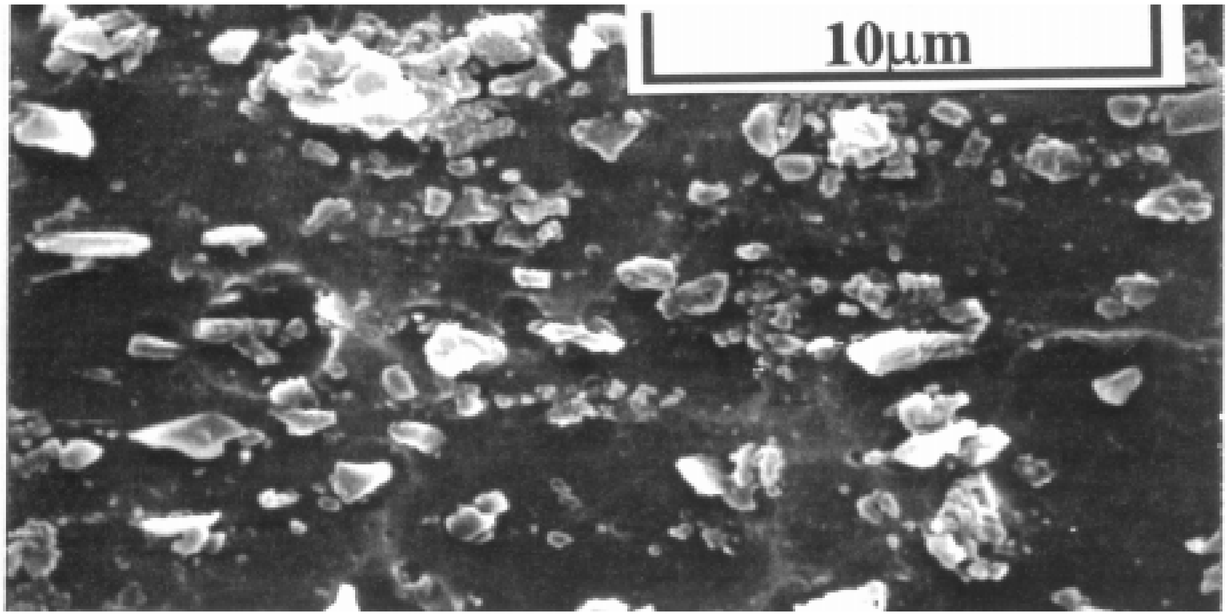

Fig.1: SEM microstructures of SiC/6061 Al composite.

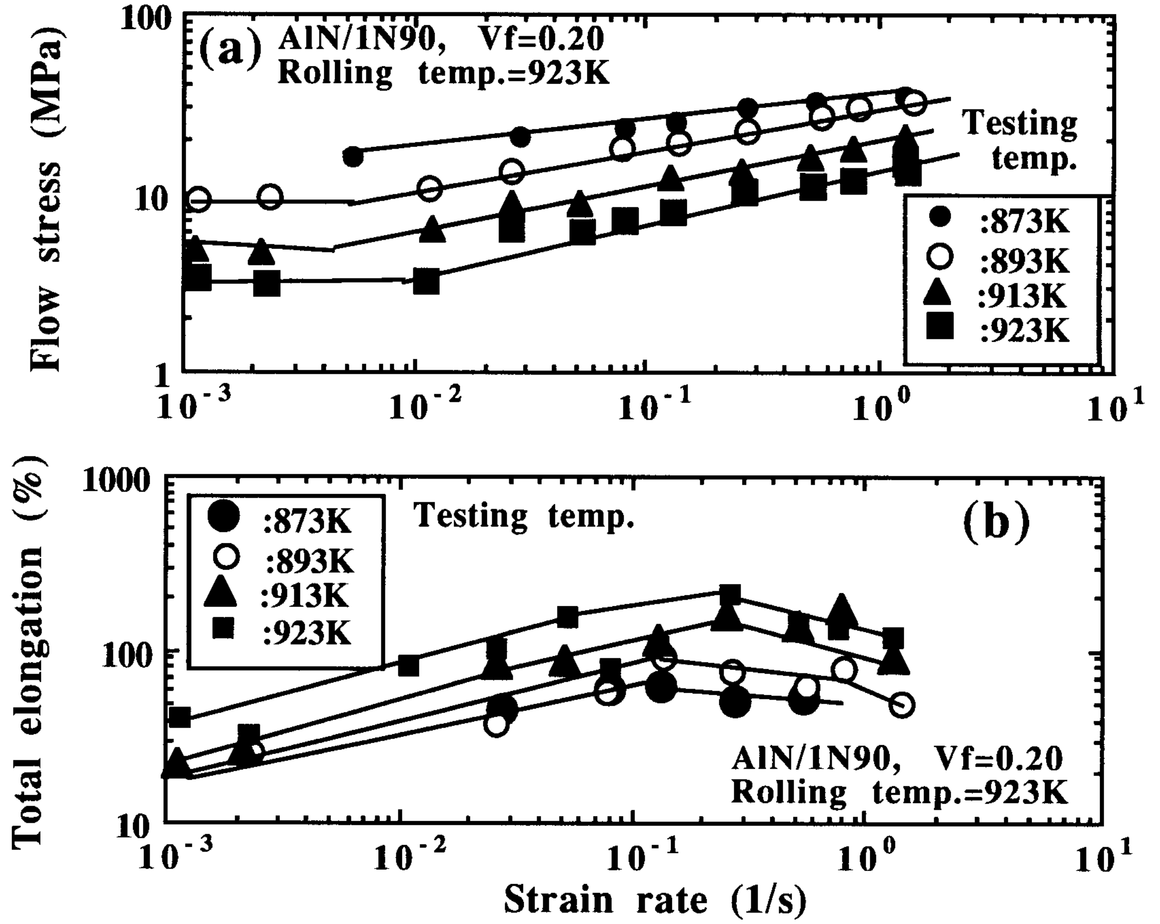

Fig.2: Superplastic characteristics of AlN/1N90 Al composite with Vf=0.20

HSRS of AlN/1N90 Al Composite

Flow stress (σ) and true strain rate ($\dot{\varepsilon}$) in a superplastic material are related via the equation $\sigma=K\dot{\varepsilon}^{m}$ where *K* is a constant, and m is the strain rate sensitivity value. The m value of a superplastic material is normally greater than 0.3 because a higher m value is expected to suppress neck formation and leads to high tensile elongation.

Superplastic characteristics of the AlN/1N90 Al composite with Vf=0.20 are shown in Fig.2(a), (b) as a function of testing temperature. The composite deformed at 873, 913 and 923K indicates the m value of about 0.3 in the strain rate range higher than 0.01 s^{-1} and also threshold stress appears in the strain rate range less than 0.01 s^{-1}. The maximum tensile elongation of about 200% in the composite was obtained at the strain rate of about 0.3 s^{-1} and at 923K which is just below melting temperature of pure aluminum. At strain rates higher than 1.0s^{-1}, the elongation value of the AlN/1N90 Al composite deformed at 923K begins to decrease although the m value still keeps 0.3.

The results indicate that the AlN/1N90 pure aluminum composite made by a powder metallurgical method before extrusion and rolling could produce HSRS by grain boundary sliding.

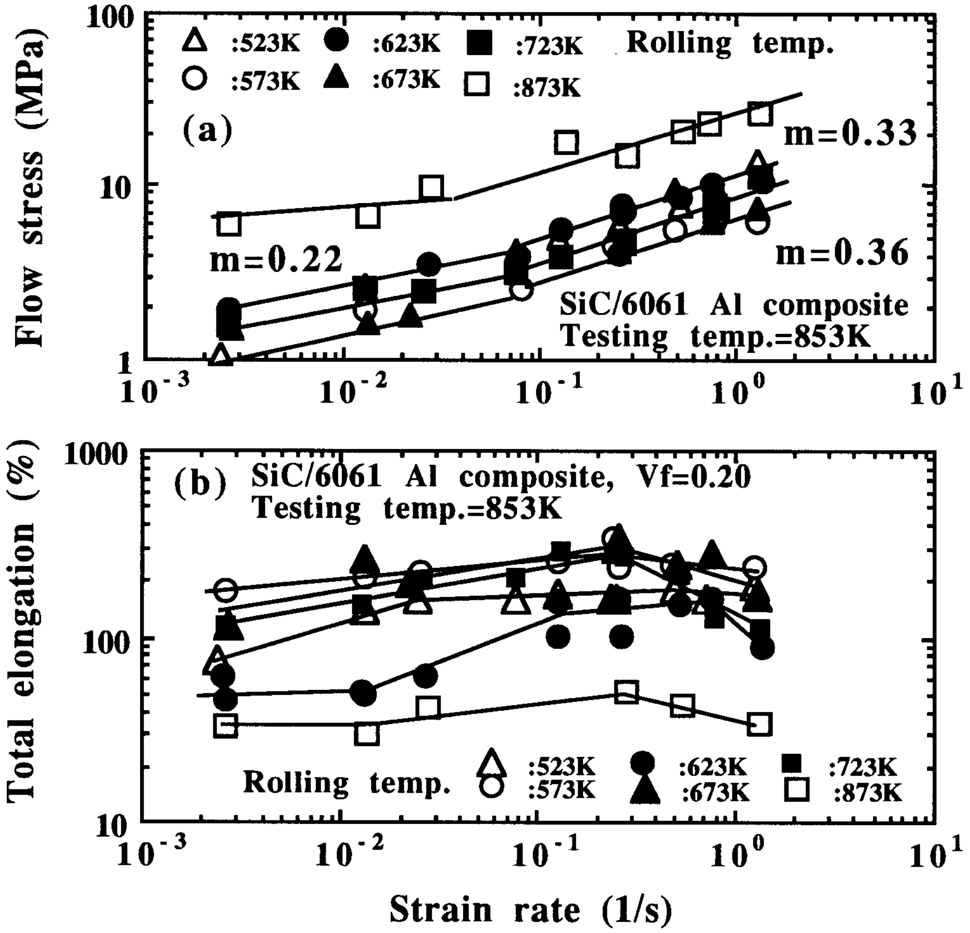

Fig.3: Effect of rolling temperature on (a)the flow stress and(b) on the total elongation of the SiC/6061 Al composite hot-rolled after extrusion and squeeze casting

Fig.3(a) shows the flow stress-strain rate relationship of the SiC/6061 Al composite fabricated by a vortex method and squeeze casting before extrusion and hot rolling as a function of rolling temperature. The flow stresses increase with increasing strain rate and the m value becomes more than 0.3 in the strain rate region from 0.1 to 1.3 s^{-1}. The flow stress in the case of 873K rolling became higher as compared with those of the composites hot-rolled below 723K because reaction between matrix and SiC may have occurred. The composites hot-rolled at 573 and 623K give lowest flow stresses. The composite made by the vortex method shows a lower m value of about 0.2 in the strain rates of less than 0.08 s^{-1}.

Total elongations of the SiC/6061 Al composites hot-rolled after extrusion, are shown in Fig. 3(b). The composites hot-rolled at 573, 623 and 723K exhibit 200~300% in the strain rate range of 0.01~0.8s^{-1}. The total elongation of the composite hot-rolled at 873K decreases to less than 50% due to reaction with SiC particles. The lower total elongation of the composite hot-rolled at 523K and 623K might be related to damage produced near or at the interface during hot rolling. For rolling temperatures of 573, 673 and 723K, the highest elongation were obtained for a strain rate of about 0.1s^{-1}.

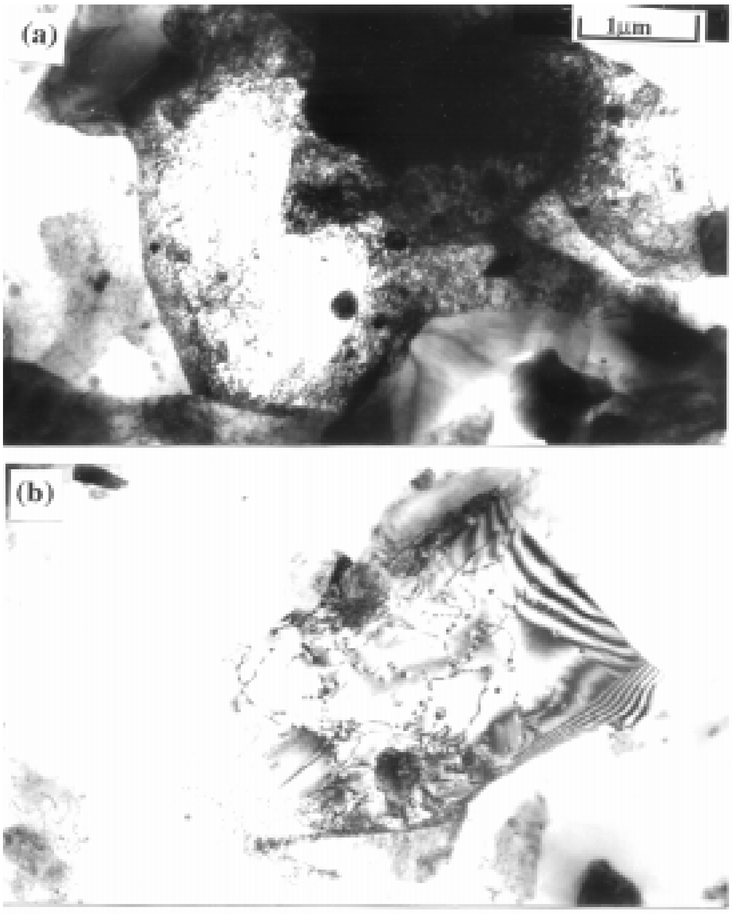

Fig.4: TEM microstructures of (a) the SiC/6061 aluminum alloy composite heated at 853K and (b) the SiC/6061 deformed superplastically

Deformation Mechanism of HSRS

Several possible deformation processes, including fine grain boundary sliding, interfacial sliding at liquid phase, and dynamic recrystallization, are expected to take place during HSRS. The m value of more than 0.3 at a relatively high strain rate of about $0.1s^{-1}$ in the AlN/1N90 Al composites indicates that the observed HSRS phenomena in the both composites occur predominantly by fine grain boundary sliding, since melting temperature of AlN/1N90 pure aluminum composite is 923.5K and the matrix in the AlN/1N90 Al composite hot-rolled after extrusion consists of a fine grain of about 2µm. Fig.4(a) shows TEM microstructure of the SiC/6061 Al composite fabricated by a vortex method, squeeze casting before extrusion and rolling. TEM micrograph of the SiC/6061 Al composites in Fig.4(b) deformed superplastically indicate that the composite consists of a fine grain of about 2µm and the grain size is thought to be stable during and after superplastic deformation.

Fig.5 shows the fracture surfaces of the SiC/6061 Al composite($\dot{\varepsilon}=0.13s^{-1}$ and $e_f=342\%$) pulled at 853K. The fracture surface of the SiC/6061 Al composites shows a partially melted matrix and a lot of filaments. The solidus temperature of the SiC/6061 composite was 836K. The solidus and melting temperature of the composite decreases due to the Mg, Si, Cu segregation at grain boundaries [9-12], so that semi-solid phase is thought to exist at the interfaces between matrix and SiC particles during superplastic deformation at 853K. The filaments could be related to a semi-solidus phase at or near an interface of the composite since this could be elongated significantly during hot rolling and superplastic deformation [9-12]. Table 3 indicates that the SiC/6061 Al composite made by a vortex method includes a lot of alloy elements which decrease the melting point of the aluminum alloy matrix. The diameters of the filaments in the SiC/6061 Al composite are very fine as the relative distance between the fine SiC with average particle size of 0.6μm is narrow. It is thought, therefore, that the interfacial sliding at the liquid phase contributes to HSRS in addition to grain boundary sliding.

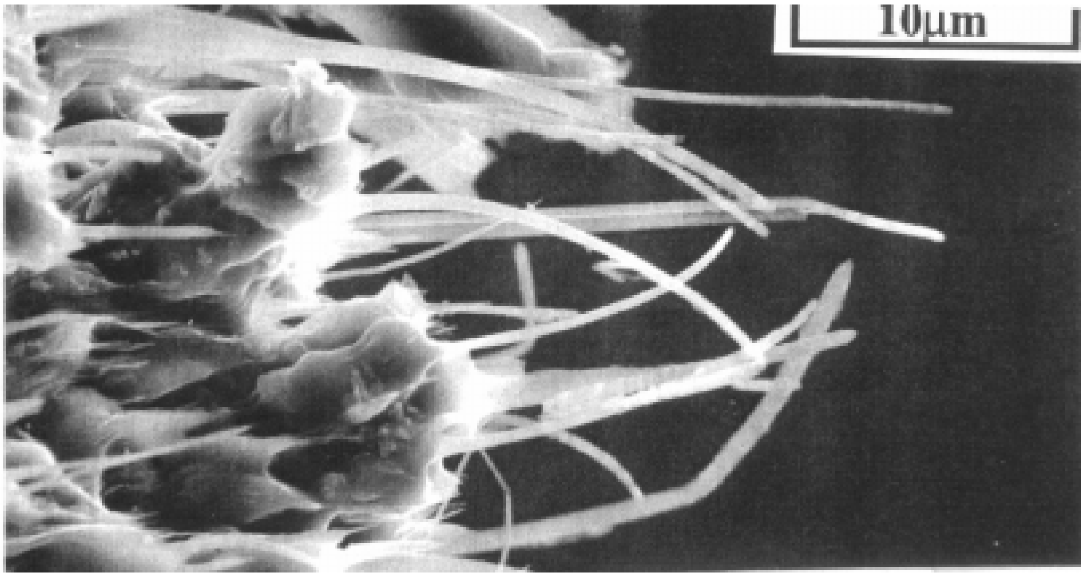

Fig.5: Fracture surface of the SiC/6061 aluminum alloy composite hot-rolled and extruded after vortex & squeeze castings

CONCLUSIONS

The superplastic characteristics of AlN/1N90 Al composite made by a powder metallurgical method and the SiC/6061 Al alloy composite fabricated by a vortex method before squeeze casting, hot-rolled after extrusion, were investigated.

(1) The AlN/1N90 PM Al composite with Vf=0.20 indicates the m value of about 0.3 in the strain rate range higher than 0.01 s^{-1} at 873, 913 and 923K.
(2) The maximum total elongation of about 200% in the AlN/1N90 PM Al composite with Vf=0.20 was obtained at the strain rate of about 0.3 s^{-1} and at 923K. The result indicates that in the case of AlN/1N90 Al composite, the HSRS could produce without help of interfacial sliding at liquid phase.
(3) The SiC/6061 Al composites hot-rolled in rolling strain per passes of 0.1 and at 573K exhibits m values of 0.4~0.6 and total elongations of 200~300% at 853K in the strain rate of 0.08~1.3 s^{-1}.
(4) The AlN/1N90 and the SiC/6061 Al composite has a fine grain of about 2μm and the fine grain size did not change after superplastic deformation.
(5) The fracture surface of the SiC/6061 Al composite has a partially liquid phase and shows filaments. It is thought that in the case of the SiC/6061 Al composite, interfacial sliding at the liquid phase contributes to the HSRS in addition to grain boundary sliding in these composites.

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