www.czasopisma.pan.pl www.journals.pan.pl

Arch. Metall. Mater. **66** (2021), 4, 941-946

DOI: 10.24425/amm.2021.136401

JIN MAN JANG[1], SE-HYUN KO[1], WONSIK LEE[1*]

EFFECTS OF SiC COATING OF CARBON FIBER ON MECHANICAL PROPERTIES IN SHORT CARBON FIBER REINFORCED Al MATRIX COMPOSITE

A356 Al composites reinforced by short carbon fiber were prepared through the 2-step process: fabrication of a composite precursor and ultrasonication of the precursor melt. The short carbon fibers were coated with 0.15~1.5 μm thick SiC layer by a carbothermal reaction, and an amount of the carbon fiber reinforcement was determined to be 1.5 vol.% and 4.0 vol.%, respectively. The addition of the carbon fiber increased the hardness of A356 alloy. However, tensile strength did not increase in the as-cast composites regardless of the SiC coating and volume fraction of the carbon fiber, due to the debonding which reduced load transfer efficiency from matrix to fiber at the interface. After T6-treatment of the composites, a significant increase in strength occurred only in the composite reinforced by the SiC-coated short carbon fiber, which was considered to result from the formation of a precipitate improving the Al/SiC interfacial strength.

Keywords: Short carbon fiber, Al composite, SiC coating, Mechanical property

1. Introduction

Carbon fiber has been adopted as a reinforcement for polymer matrix composites used in automotive and aerospace industries because of its low density, high strength and stiffness, low thermal expansion, and low chemical reactivity [1]. These merits have also expanded the application of carbon fiber to the field of metal matrix composite (MMC), especially aluminum matrix composite for high specific strength and stiffness [2]. Al matrix composites reinforced by carbon fiber has been manufactured mainly by liquid-based process due to low cost and simplicity in process, and the methods are classified largely into stir casting using short carbon fiber (SCF) [3-5] and infiltration of liquid aluminum into a preform of continuous (long) carbon fiber [6,7]. The composites reinforced by the continuous fiber show generally superior mechanical properties due to continuity and high volume fraction of fiber [8], but the shape of a product is limited in complexity depending on the shape of the preform. In this regard, the casting method using SCF is much useful in manufacturing the complex-shaped Al-CF composite components.

In manufacturing the carbon fiber reinforced aluminum composite by stir casting, the poor wettability between aluminum and carbon fiber causes insufficient dispersion, resulting in the agglomeration of SCFs and the formation of micro-void at between the agglomerated fibers due to lack of filling [3,4]. Also, the formation of a brittle Al_4C_3 phase due to reaction at the interface between liquid Al and SCF decreases the mechanical properties in the composite [9]. As a method to improve the wettability and stability at the interface, many researchers have focused on various coating materials of carbon fiber [5,10,11] and silicon carbide (SiC) coating can be a good candidate. SiC has relatively low contact angle of 79° at 973 K with the molten Al (relatively better wettability) [12], and SiC particulate has been used as a useful reinforcement for aluminum matrix composite although SiC forms the Al_4C_3 phase at the interface due to reaction with Al matrix. However, the formation of Al_4C_3 in SiC composite can be suppressed effectively with a reduction of process temperature [13] and an increase of Si content in Al matrix [14]. I.-H. Kim et al. [15] have observed in SEM-EDS analysis that SiC coating layer on carbon fiber was stable without notable degradation for 180 min in pure Al melt of 973 K and for 30 min at 1073 K. Also, Y. Liu and B. Kindl [16] reported that the Al_4C_3 phase was not formed at 1023 K in Al-6.5wt%Si alloy through the re-formation of SiC by the reaction of the formed Al_4C_3 phase with silicon in the molten Al alloy. From the above results, it was expected that it would be possible to improve the wettability and to suppress the formation of the Al_4C_3 phase by

1 ADVANCED MATERIALS AND PROCESS R&D DEPARTMENT, KOREA INSTITUTE OF INDUSTRIAL TECHNOLOGY, INCHEON 21999, REPUBLIC OF KOREA

* Corresponding author: wonslee@kitech.re.kr

coating SiC on the SCF and lowering the casting temperature of SCF reinforced composites with high Si content.

In this study, as a part of basic research on A356 Al (6.5~7.5wt.%Si) composite reinforced by SiC-coated short carbon fiber, the effects of SiC coating on mechanical properties were investigated in the composites fabricated at the temperature of maximum 973 K using a 2-step casting process.

2. Experimental

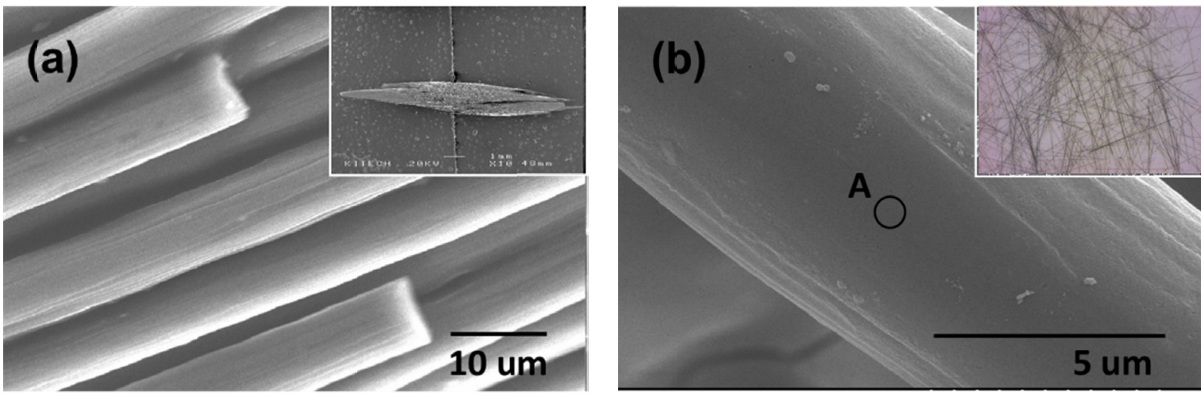
Bundles of the short carbon fiber with about 7 μm in diameter and a few mm in length (TENAX 201-Pelletized Chopped Product, Toho Tenax America, Inc.) were used as a starting reinforcement material. The bundles were separated into individual short fibers by ultrasonic cavitation for 5 hrs in acetone. Some short fibers were dispersed again in silica sol and dried in air, resulting in silica-coated carbon fibers. A carbothermal reduction of the silica coating layer to silicon carbide (SiC) was performed for 1 hr at 1773 K in argon atmosphere, followed by furnace cooling. SCF reinforced A356 Al composites were manufactured through a 2-step process using the uncoated and the SiC-coated SCFs, respectively. As the first step, the SCFs were fabricated to a very thin sheet with a mesh (net)-like structure, and the thin fiber sheets and 2 mm thick A356 Al plates were alternately stacked so that the volume of fiber was 1.5 vol.% and 4.0 vol.%, respectively. Subsequently, to fabricate a bulk composite precursor, they were heated to 933 K above the melting point (830~886 K) of A356 in a chamber filled with argon gas, while being pressed by the dead weight of 1kg. As the second step to disperse the SCFs homogeneously in A356 Al matrix, the bulk composite precursors were re-melted at 973 K in a graphite crucible under Ar environment, then, an ultrasonic wave was applied into the melt for 10 min. The as-cast composites were solution-treated for 210 min at 803 K and T6-treated for 180 min at 428 K.

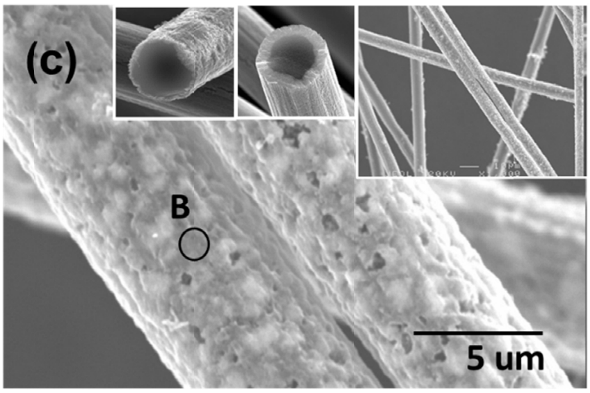
The effects of SiC coating on mechanical properties were investigated using Vickers hardness tester and tensile test machine. Vickers hardness test (HM-21, Mitutoyo, Japan) was performed for 30 sec in 10 g force, and tensile test (DTU-900MHA, Daekyung, Korea) at a strain rate of 5×10^{-3} s^{-1}.

3. Results and discussion

3.1. Production of composites

Fig. 1 shows the SEM micrographs of fibers at each step in the process of forming the SiC coating layer. Fig. 1(a) is an image of a chopped bundle of SCFs with about 7 μm diameter. After ultrasonication in acetone and silica sol, each fiber was coated by nano-sized silica, showing a smooth surface (Fig. 1(b)). By subsequent carbothermal reduction reaction of silica layer with carbon fiber, the silica coating layer was transformed to the SiC one (Fig. 1(c)) and EDS results on each surface indicate





EDS analysis

	A	B
Element	wt.%	wt.%
C K	35.22	48.85
O K	36.47	-
Si K	27.45	51.15
Na K	00.85	-
Totals	100.00	100.00

Fig. 1. SEM micrographs of (a) as-received (bundle), (b) silica-coated and (c) SiC-coated short carbon fibers. EDS analysis was carried out on the surface of the carbon fiber in (b) and (c), respectively

the formation of SiC due to the reaction. The thickness of the SiC layer was measured in the range from 150 nm to 1.5 μm [8].

In this study, four kinds of composites and an A356 Al ingot as a reference material were prepared through the 2-step casting process, and the compositions of the composites are shown in Table 1. The small amount of SCF of 1.5 and 4.0 vol.%, respectively, were chosen to maximize the effect of SiC coating while minimizing that of volume fraction on mechanical properties. Fig. 2 shows the optical micrographs of the as-cast composites containing the uncoated and SiC-coated SCF reinforcement dispersed by ultrasonic wave. The SCFs were separated well into individual fibers without any clusters unfilled by A356 melt, indicating that the ultrasonication was very useful in dispersing SCFs.

TABLE 1

The compositions of the composites produced in this study

Designation	Matrix	Volume of SCF (%)	Coating
A356	A356	—	—
Al-1.5CF	A356	1.5	uncoated
Al-4.0CF	A356	4.0	uncoated
Al-S1.5CF	A356	1.5	SiC coated
Al-S4.0CF	A356	4.0	SiC coated

3.2. Mechanical Properties of composites

Mechanical properties in a composite material are affected by volume fraction of a reinforcement, type of a reinforcement such as species, size and aspect ratio, characteristics of an interface such as a reaction and bonding strength, and lattice coherency at the interface such as incoherency and semi-coherency. From the viewpoint of lattice coherency at the interfaces, Al matrix and the SiC layer are possible theoretically to form the semi-coherent interface with lattice mismatch of 0.071 whereas the Al/CF interface is incoherent, considering the habit planes and lattice constants among Al (fcc, lattice constant 0.405 nm), SiC (fcc, lattice constant 0.436 nm) [17] and CF (graphite-like structure, d_{200} 0.344 nm) [18,19]. However, the grain size of SiC formed by carbothermal reduction is as small as under 100 nm [17]. Thus, a number of the small SiC grains in the coating layer have random orientations, resulting in forming the incoherent Al/SiC interface with no specific habit plane. Also, the shape and size of the SCF reinforcement used in this study are the same in the four composites. As a result, in this work, the effects of shape, size, and interfacial incoherency was not considered in comparing on mechanical property, and the effects of SiC coating was discussed mainly in point of characteristics of the interface such as bonding strength and the formation of flaw.

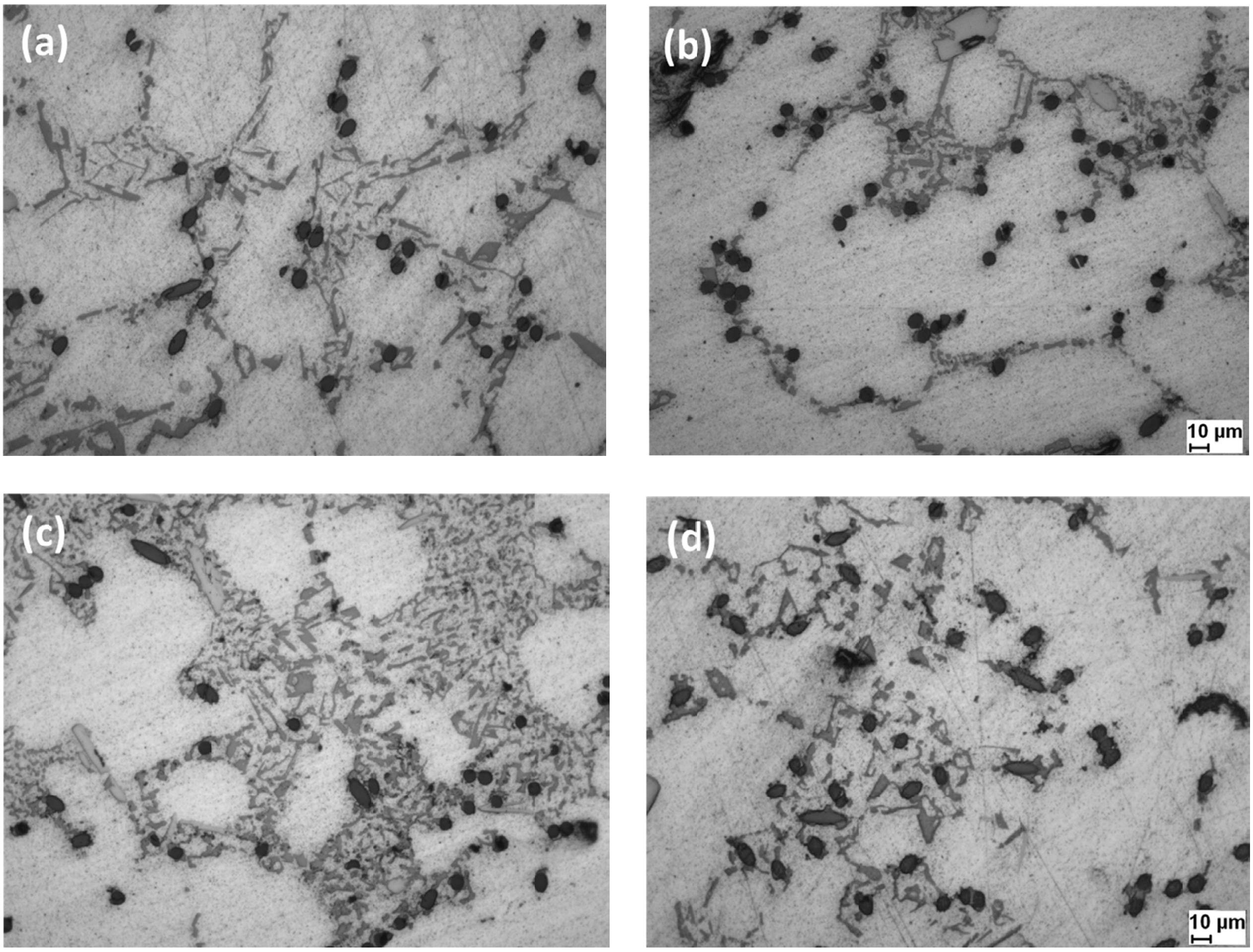


Fig. 2. Optical micrographs of as-cast composites containing uncoated and SiC-coated short carbon fiber reinforcement dispersed by ultrasonic wave. (a) Al-1.5CF, (b) Al-4.0CF, (c) Al-S1.5 and (d) Al-S4.0CF

3.2.1. Tensile strength

Table 2 summarizes the mechanical properties in as-cast and T6 treated composites, respectively. In cases of the as-cast composites, as seen in Table 2, the addition of SCF reinforcement did not influence the strength and deformation behavior regardless of SiC coating and SCF volume fraction. This means that the lack of fiber reinforcing efficiency is due to the debonding by weak bonding strength between Al matrix and carbon fiber. During tensile plastic deformation of the Al-SCF composite materials, high shear stress occurs at the interface due to the difference of stiffness between Al matrix and SCF reinforcement. At this time, if the bonding strength is low at the interface, the stress will cause the debonding due to the formation of void and/or cracking at the interface after yielding of Al matrix (but, SCF still behaves elastically). The debonding reduces a load transferability from matrix to fiber at the interface, resulting in a decrease of the strengthening effect by SCF reinforcement. As seen in Table 2, the tensile strength was not increased in the as-cast Al-S1.5CF and Al-S4.0CF including SiC-coated SCF, either. According to the report of A.C. Ferro and B. Debby [14], the wettability between Al and SiC increased at a temperature above 1273 K. Based on this, it is considered that the wettability improvement by SiC coating could not occur in the composite materials of this study that were ultrasonic-treated at 973 K and solidified. SEM images of fracture surfaces are shown in Fig. 3. Fig. 3 (a) and (b) are the representative SEM images in uncoated SCF reinforced composites, Al-1.5CF and Al-4.0CF. Al matrix and SCF were separated cleanly and clearly at the interface between them. Also, as shown in Fig. 3(b), the fiber was pulled out, and a crevice was formed at the interface, resulting from the difference in deformation between matrix (plastic) and SCF (elastic). These SEM images clarify that the debonding interrupted a load transfer from matrix to fiber, suppressing the strengthening effect by SCF.

On the other hand, the tensile strengths in T6-treated composites increased overall due to precipitation hardening of the Al matrix (see Table 2). Fig. 4 shows the tensile stress-plastic strain curves in T6-treated composites. As can be seen in Fig. 4(a), in the composite materials including uncoated SCF, the strength increase by the reinforcement did not occur at all even after the T6-treatment, indicating that the bonding characteristics at the interface was not improved by the T6-treatment. However, a remarkable increase in strength was observed in the T6-treated composites reinforced by SiC-coated SCF, as shown in Fig. 4(b). This improvement means that the interface is strengthened enough to transfer load from matrix to SCF by T6-treatment. Indeed, as seen in the fracture surface of Fig. 3(c), the Al/SiC interface was still bonded until the fracture of the specimen, and rather, the debonding occurred at the SiC/CF interface. W.Q. Song et al. [20] have observed the formation of a precipitate by aging at the interface between Al6061 matrix and SiC particle, and H. Ribes et al. [21] reported a spinel phase ($MgAl_2O_4$) formation at the A356/SiC interface. P. Liu et al. [22] have observed in detailed TEM analyses that the $MgAl_2O_4$ phase was formed at the interface in Al2024/SiC particulate composite fabricated by powder metallurgy (hot pressing at 853 K), and both interfaces of Al/$MgAl_2O_4$ and

TABLE 2

Tensile properties of the composite materials

	As-cast			T6-treated			
	YS (MPa)	UTS (MPa)	Plastic Elongation(%)	YS (MPa)	UTS (MPa)	Plastic Elongation(%)	Hardness (HV, 10g)
Al	97.3	168.4	4.2	122.3	194.9	5.3	62.8
Al-1.5CF	101.8	175.4	5.3	119.7	200.6	4.7	81.2
Al-4.0CF	104.7	171.3	4.3	119.1	199.2	4.5	82.1
Al-S1.5CF	97.6	169.1	4.7	172.0	232.3	4.9	109.1
Al-S4.0CF	100.9	176.7	5.6	186.9	246.7	4.5	113.1

* All values are the average ones measured from three specimens

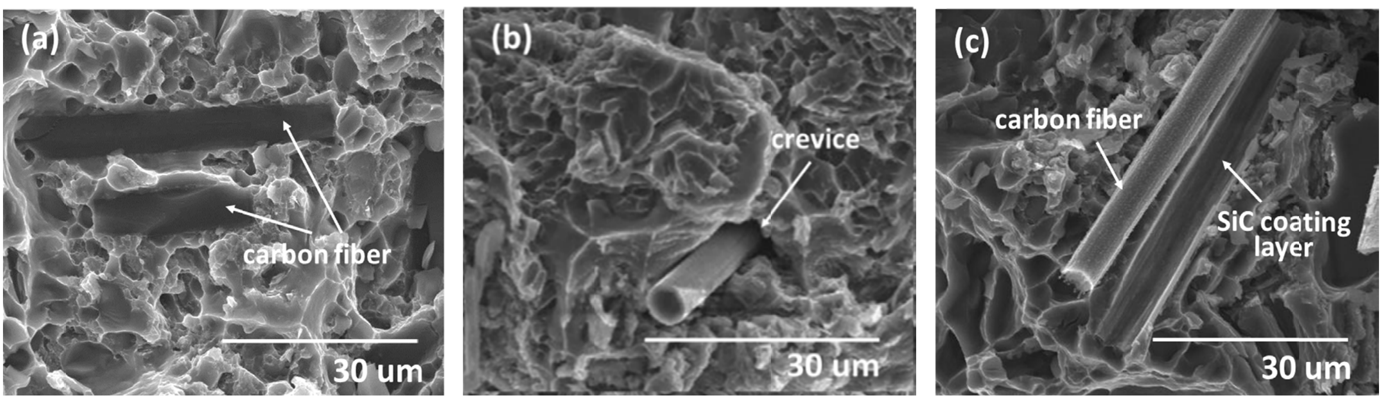


Fig. 3. SEM images of fracture surfaces after tensile test. (a) as-cast Al-1.5CF, (b) as-cast 4.0CF and (c) T6-treated Al-S4.0CF

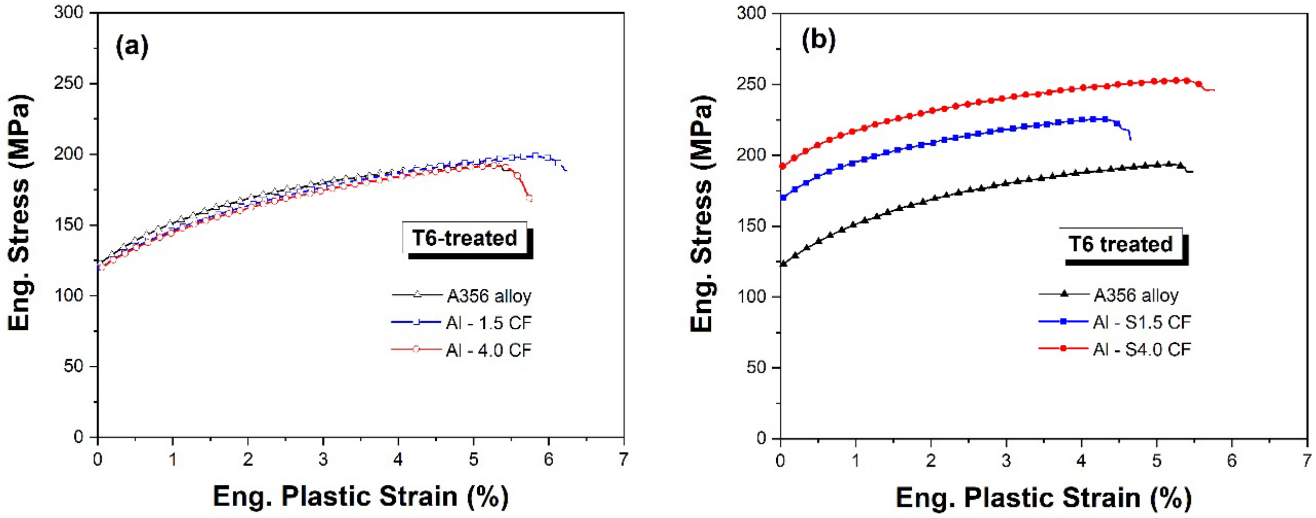


Fig. 4. Representative tensile stress vs. plastic strain curves in T6-treated composites reinforced by (a) uncoated and (b) SiC-coated short carbon fibers

$MgAl_2O_4$/SiC had semi-coherency, implying that the formation of the $MgAl_2O_4$ can contribute to the increase in strength. From these observation results, it could be deduced carefully that the remarkable strengthening of the Al/SiC interface resulted from the formation of a precipitate phase at the interface by T6-treatment, and considering the elongations, the interface was strengthened enough to endure the flow stress during the tensile test.

3.2.2. Vickers hardness

Vickers hardness values in the T6-treated composites are shown in Table 2. Unlike the tensile test results, hardness increased even in uncoated SCF reinforced composites, which resulted from compressive deformation behavior in hardness test. When a load is applied to the indenter of the Vickers hardness tester, the material around the indenter is subjected to compressive stress, and in the compressed state, the debonding due to the formation of cracks or voids at the interface is highly suppressed. As a result, the SCF acted as a barrier against the deformation of the Al matrix regardless of SiC coating, resulting in an increase of hardness. These Vickers hardness results support obviously that the reason why the tensile strength did not increase in the T6-treated composite including uncoated SCF (Fig.4 (a)) is the debonding due to low interfacial strength.

4. Conclusion

In this study, the short carbon fiber (SCF) reinforced A356 Al composites were manufactured by casting method using ultrasonic wave, and the effects of SiC coating of SCF on mechanical properties were investigated.

The ultrasonication was effective in dispersing SCFs in Al melt, and the composites in which SCFs were dispersed evenly were manufactured without mechanical stirring. In the as-cast composites, an increase of tensile strength by SCF reinforcement did not occur regardless of the SiC coating, which resulted from the interruption of load transfer efficiency from matrix to fiber due to the debonding at the Al/SCF interface. However, after T6-treatment, the SiC-coated SCF reinforced composite exhibited a significant increase in strength, and this improvement was considered to be due to the formation of a precipitate strengthening the interface between A356 matrix and SiC coating layer.

Acknowledgments

This study has been conducted with the support of the Korea Institute of Industrial Technology as "Development of root technology for multi-product flexible production (kitech EO-20-0015)"

REFERENCES

[1] X. Huang, Materials **2**, 2369 (2009).
[2] J.W. Kaczmar, K. Pietrzak, W. Wlosinski, J. Mat. Proc. Tech. **106**, 58 (2000).
[3] H. Naji, S.M. Zebarjad, S.A. Sajjadi, Mater. Sci. and Eng. A **486**, 413 (2008).
[4] C.P. Ju, K.I. Chen, J.H. Chern, J. of Mat. Sci. **29**, 5127 (1994).
[5] S. Ciby, B.C. Pai, K.G. Satyanarayana, V.K. Vaidyan, P.K. Rohatgi, J. of Mat. Eng. and Perf. **2** (3), 353 (1993).
[6] W.G. Wang, B.L. Xiao, Z.Y. Ma, Comp. Sci. Tech. **72** (2), 152 (2012).
[7] A. Daoud, Mater. Sci. and Eng. A, **391**, 114 (2005).
[8] C.-W. Lee, I.-H. Kim, W. Lee, S.-H. Ko, J.-M. Jang, T.-W. Lee, S.-H. Lim, J.P. Park, J.D. Kim, Surf. Interface Anal. **42**, 1231 (2010).
[9] S.-H. Li, C.-G. Chao, Metall. Mater. Trans. A **35** (7), 2153 (2004).

[10] E. Hajjari, M. Divandari, A. Mirhabibi, Mater. Des. **31** (5), 2381 (2010).
[11] L. Aggour, E. Fitzer, M. Heym, E. Ignatowitz, Thin Solid Films **40**, 97 (1977).
[12] S. Bao, K. Tang, A. Kvithyld, T. Engh, M.Tangstard, Trans. Nonferrous Met. Soc. China **22**, 1930 (2012).
[13] T. Iseki, T. Kameda, T. Maruyama, J. Mater. Sci. **19** (5), 1692 (1984).
[14] A. C. Ferro, B. Debby, Acta Metal. Mater. **43** (8), 3061 (1995) .
[15] I.-H. Kim, W. Lee, C.-W. Lee, S.-H. Ko, J.-M. Jang, Surf. Interface Anal. **42** (6-7), 743 (2010).
[16] Y. Liu, B Kindl, Scr. Metall. Mater. **27** (10), 1367 (1992).
[17] H. Abderrazak, E.S.B.H. Hmida, R. Gerhardt (Ed.), Silicon carbide, InTech, Rijeka 316, Croatia (2011).
[18] D.L. Chung, Butterworth-Heinemann, Carbon Fiber Composites, Boston 1994.
[19] J.G. Morley, Academic Press, High-Performance Fiber Composites, Orlando 1987.
[20] W.Q. Song, P. Krauklis, A.P. Mouritz, S. Bandyopadhyay, Wear **185**, 125 (1995).
[21] H. Ribes, R.D. Silva, M. Suéry, T. Bretheau, Mater. Sci. and Tech. **6**, 621 (1990).
[22] P. Liu, A.-Q. Wang, J.-P. Xie, S.-M. Hao, Trans. Nonferrous Met. Soc. China **25**, 1410 (2015).