1 Introduction
Nano carbon materials such as carbon nanotubes (CNTs), carbon nanofibers (CNFs), and graphene have been promising reinforcements for light metallic matrices due to their excellent specific strength, specific modulus, and thermal and electrical conductivities [1-3]. However, fabrication of nano carbons reinforced metal matrix composites (MMCs) is very challenging due to their poor wettability [4]. Because of the difficulties in introducing carbon materials into metal melts, most work used powder metallurgy (PM) routes [5]. When fabricating nano carbons reinforced metal matrix composites (MMCs), they are critical issues to disperse the nano carbons in metallic melt and to maintain the stability of nano carbons under atmosphere due to strong reactivity of carbon with oxygen. In order to improve the stability of nano carbons and the wettability between nano carbons and metallic melt, Nano carbons have been coated with metal and/or oxide [6]. The squeeze casting process, one of the conventional casting methods for composites, has merits such as high productivity and easiness for near-net-shape fabrication, but it has shortcomings of poor reliability, requirement of high-pressure loading of 50 MPa or more in order to fabricate high volume and ultra-fine particles reinforced metallic composites by enhancing the wettability between reinforcements and matrix. To fabricate effectively the metal matrix composites reinforced with nano carbons, it is thus necessary to introduce new-concept fabricating process, one of which is a liquid pressing process [6-7] using relatively low pressure near to the theoretically required minimum loading pressure. In the process, it is possible to fabricate large and thin-plate-type composites and control the microstructure and phase of the matrix.

In this study, nano carbons reinforced aluminium alloy (A356) composites have been fabricated successfully by the uniform mixture of nano carbons (CNFs) and SiC particles (SiCp) and the unique casting method of liquid pressing process. The CNFs and SiCp were uniformly mixed by wet mixing process with surfactant. Microstructure of the composites has been analyzed. The mixture of CNFs and SiCp were dispersed homogeneously in the matrix. Their mechanical properties have also been evaluated by tensile and compressive tests.

2 Experimental
The vapor grown carbon nanofibers (CNFs) supplied by Showa Denko (Japan) were used as the reinforcements. Also, silicon carbide particles supplied by Nilaco (Japan) were additional reinforcement. A356 aluminium alloy was a matrix. Physical and mechanical properties of CNFs, SiCp and A356 were summarized in table 1.

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<tbody>
<tr>
<td>CNF</td>
<td>2.0</td>
<td>240 – 400</td>
<td>3.000</td>
<td>150–200</td>
<td>-10</td>
</tr>
<tr>
<td>SiCp</td>
<td>3.21</td>
<td>430</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>A356</td>
<td>2.69</td>
<td>72</td>
<td>220</td>
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The uniform mixture of CNFs and SiCₚ was prepared by simple sonication process with surfactant. Firstly, the ethanol suspension (1 L) of carbon nanofiber of 25.0 g was prepared by sonication for 30 min. After preparing the CNFs suspension, silicon carbide particles of 79.25 g were added and then sonicated again for 30 min. Finally, 25.0 g of cetyltrimethylammonium bromide was added and mixed by sonication for 1 hr. The mixture of CNFs and SiCₚ was obtained by filtrating suspension, washing by ethanol, and drying in vacuum oven for 12 hrs.

The CNFs and SiCₚ reinforced A356 composites were fabricated by the liquid pressing process [6-7]. The mold interior was sized by diameter φ 120 mm × thickness t 10 mm. The CNFs and the prepared mixture of CNFs and SiC particles were inserted with A356 master alloy plates into the mold, degassed, and evacuated by a mechanical vacuum pump. The mold was heated to 750°C, held for 5 minutes, and then pressed under a pressure of below 20 MPa. The fabricated composites were sectioned, polished for scanning electron microscope (SEM) observations. The composites were also machined into sub-sized dog-bone and rectangular shape specimens for tensile and compressive tests.

3 Results and discussion

Table 2 shows the list of the wetting angle between aluminium melt and various reinforcements of oxides, carbides, and carbon. The wetting angle between carbon and aluminium is 157° at 800 °C. At the melt temperature of 750 °C which is processing temperature of aluminium alloy, the wetting angle between carbon and aluminium is over 160°. The poor wettability of carbon by aluminium is most critical obstacle in casing route to fabricate the nano carbons reinforced aluminium composites. The aforementioned problems of the dispersion of carbon nanoparticles in metallic melt and the stability of nano carbons under atmosphere due to strong reactivity of carbon with oxygen are also critical issues. These all factors make the fabrication of the carbon nanoparticles reinforced aluminium alloy matrix composites a difficult task, and result in poor mechanical properties.

Table 2 list of the wetting angles between aluminium melt and various reinforcements. [8]
Carbides such as silicon carbide (SiC) and titanium carbide (TiC) is also not wettable with aluminum melt, but the wetting angle between the carbides and Al melt is lower than that of carbon. It is anticipated that mixing process of SiCs and/or TiCs with nano carbons can be a simple and effective route to overcome the problem of casing process to make the carbon nanoparticles reinforced Al matrix composites.

Fig. 2 shows the compaction and infiltration mechanism of non-wettable (wetting angle > 90°) reinforcing particles in metallic melt. As pressure applied in the melt, the particles are compacted and the volume fraction increases. Above the critical infiltration pressure, the metallic melt is infiltrated into the gap among the compacted particles, and then the particles are swelled.

Fig. 3. Calculated results of minimum infiltration pressure of aluminium alloy melt into nano carbon preforms as functions of surface tension, particle size at wetting angle of 150° and wetting angle at particle size of 15nm.
Fig. 3 shows the results of minimum infiltration pressure of aluminium alloy melt into nano carbon preforms. From preliminary experiments of fraction of the preform of nano carbons increased approximately 55% due to compaction by applied pressure. In case of a change in particle size, the minimum infiltration pressures of CNTs (15nm) and CNFs (150nm) were about 90MPa and 9MPa, respectively. As a decrease of wetting angle of 110°, the infiltration pressure decreased from 90MPa to 35MPa. The decrease of minimum infiltration pressure was relatively small by the change of surface tension.

Fig. 4. SEM images of mixture of CNFs and SiC\textsubscript{p} at (a) low- and (b) high-magnification.

Fig. 5. SEM images: (a) and (b) CNFs reinforce A356 composite; (c) and (d) CNFs + SiC\textsubscript{p} reinforced A356 composites.
Table 3. Mechanical properties (elastic modulus, tensile strength, and compressive strength) of CNFs and SiCp reinforced A356 composite comparing with A356 alloy.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Elastic modulus (Gpa)</th>
<th>Tensile strength (Mpa)</th>
<th>Compressive strength (MPa)</th>
</tr>
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<tbody>
<tr>
<td>A356</td>
<td>72</td>
<td>220</td>
<td>210</td>
</tr>
<tr>
<td>CNFs+SiCp/A356</td>
<td>104</td>
<td>261</td>
<td>585</td>
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Fig. 4 (a) and (b) show low and high magnification SEM images of mixture of CNFs and SiCp. Entanglements of as-received CNFs were dispersed and separated by the piece and CNFs and SiCp are also uniformly distributed. Mixture of CNFs and SiCp reinforced A356 composite was fabricated by the liquid pressing process. Also, only CNFs reinforced composite was fabricated to verify the feasibility of liquid pressing process and to compare the soundness of microstructure and the mechanical properties. Fig. 5 (a) and (b) show low and high magnification SEM micrographs of only 10 vol. % CNFs reinforced A356 composite. There were lot of CNFs clusters and most CNFs were not wetted with aluminium alloy even though small amount of alloy melt was infiltrated into some CNFs cluster. Fig. 4 (c) and (d) show low and high magnification SEM micrographs of 10 vol. % CNFs and 10 vol. % SiCp reinforced A356 composite. The reinforcements of CNFs and SiCp were uniformly dispersed and homogeneously distributed in the aluminium matrix. The defects formed by misinfiltration or reaction products formed by interfacial reaction at fiber/matrix interfaces are hardly found. The physical and mechanical properties were summarized in Table 3. The elastic modulus of composite of 104 GPa is about 50% higher than that of A356 alloy. Also, the compressive strength was also much higher from CNFs and SiCp reinforcements, even though the tensile strength was increased slightly.

4 Summary

Nano carbons reinforced aluminium (Al) alloy composites have been fabricated successfully by the uniform mixture of nano carbons and SiC particles and the unique casting method of liquid pressing process. The CNFs and SiCp were uniformly mixed by wet mixing process coupled with surfactant. In liquid pressing process, Al alloy melts have been pressed hydrostatically and infiltrated on nano carbons surfaces. Microstructures of the composites have been analyzed. The mixture of CNFs and SiC were dispersed homogeneously in the matrix. The modulus and strength of the composites were improved by the reinforcement of CNFs and SiCp.

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References