APPENDIX
Numerical Study of Functionally Graded Materials

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Abstract One-dimensional comprehensive mathematical model coupling particle movement and thermal conduction in the casting mould system is developed. A formula for pressure in liquid metal during the centrifuge process is derived. The model takes into consideration the propagation of solidification front and movement of particles due to centrifugal acceleration which takes place either in the same or in opposite direction to that of the solidification front depending on the relative density difference between the particles and melts. In the force balance expression, repulsive force term is incorporated for the particles that are at the vicinity of the solid/liquid interface to calculate the particle segregation pattern in the casting region. The effects of various process parameters such as, rotational speed of the mold, size of the reinforcing material, relative density difference between the particle and melt, initial pouring temperature of the liquid melt, mold pre-heating temperature, heat transfer coefficient between the casting/mold interface are studied. It is noted that for a given set of operating conditions, the thickness of the particle rich region in the composite decreases with increase in rotational speed, particle size, relative density difference between the particle and melt, initial pouring temperature and initial mold temperature. With decrease in the heat transfer coefficient between the casting/mold interface, the solidification time increases which, in turn, results in more intense segregation of solid particulates. Again, with increase in the initial volume fraction of the solid particulates, both the solidification time as well as the final thickness of the particulate rich region increase.

1. Introduction
Functionally graded materials (FGMs) have received considerable attention because of their superior properties as compared to those of most conventional metal matrix composites [1]. FGMs have a great potential for the use in automobile, aerospace, electronic and defense industries. The FGMs with aluminum matrix are used, for instance, in electronic packaging industry, for brake rotor assemblies in automobile industry, as armor materials, etc [2]. A one-dimensional comprehensive mathematical model coupling particle movement and thermal conduction in the casting/mold system is developed. A formula for pressure in liquid metal during the centrifuge process is derived. The model takes into consideration the propagation of solidification front and movement of particles due to centrifugal acceleration which takes place either in the same or in opposite direction to that of the solidification front depending on the relative density difference between the particles and melts. In the force balance expression, repulsive force term is incorporated for the particles that are at the vicinity of the solid/liquid interface to calculate the particle segregation pattern in the casting region [3]. The objective of the research work is to optimize the centrifugal casting parameters for preparation of FGMs.

2. Mathematical Model
It is known that the motion of particles in a viscous liquid under a centrifugal force obeys the Stokes’ law [4]. The viscous drag force acting on each particle varies as a function of the radius position of the ring and the equation of particles motion in a viscous liquid can be written as

$$\frac{dx}{dt} = \frac{|\rho_p - \rho_m| GgD_p^2}{18 \eta}$$

(1)
Where \( dx/dt, \rho, G, g, D, \) and \( \eta \) are velocity, density, \( G \) number, gravitational acceleration, particle diameter and viscosity of the molten metal, respectively. The subscripts 'p' and 'm' denote particle and matrix, respectively. The \( G \) number is represented as:

\[
G = \frac{4 \pi^2 N^2 r}{g} \quad (2)
\]

Where \( r \) is distance from the rotation axis and \( N \) is the velocity of rotation. During the fabrication of metallic FGMs rings with solid particles, particles in molten metal assume stable and behave as suspensions in a viscous liquid [5]. FGMs have variation of composition over a geometrical length and the effect of composition gradient of particles on viscosity must be taken into account. Eq (1) can be rewritten considering the variation of viscosity as:

\[
\frac{dx}{dt} = \frac{C\rho_p - \rho_m G\rho D^2_p}{f(v)} \quad (3)
\]

Where \( C \) is the constant and given by:

\[
C = g / 18\eta_0 \quad (4)
\]

and \( f(v) \) is a function of volume fraction of particles, \( V \), relates to variation of viscosity,

\[
f(v) = \frac{1}{(1-v/V_{max})} \quad (5)
\]

where \( V_{max} \) is the maximum containable fraction of particles and \( \eta_0 \) is viscosity of melt without particles [6]. It is known that the viscosity of the melt varies depending on the volume fraction of particles in the melt. However, it is difficult to evaluate the volume fraction of particles microscopically in an FGMs ring because of compositional gradient. Therefore, the variation of viscosity in an FGMs ring on a macroscopic scale is represented by considering a mean value at an equal width zone of ring thickness along the radial direction. This means that continuous problem is calculated as discrete one, in other word, the calculation is done assuming the FGMs to be comprised of layers.

3. Results and Discussion

During the process of casting, reinforcement particle are formed via diffusion of alloying elements. As the reinforcement elements diffuse, alternative regions with different transformation characteristics are created. The movements of particles are calculated and the weight percentage at each zone is summarized at representative relative times of 100, 200 and 300 \( \Delta t \) as a function of normalized thickness where zero and one correspond to the FGM ring inner and outer surface, respectively. The variation of volume fraction distributions for each particle in case of specimen shown in Fig 1 represent independently the volume fractions of the large and small particles, respectively, to examine the effect of combination of particle size and density on migration rate. The volume fraction increases continuously at the outer periphery with the progress of relative time in case of the large particle. The tendency is different in case of small particle. Initially, the volume fraction of the small particle increases toward the outer periphery with the relative time, however, the volume fraction have a small peak at the normalized thickness 0.6–0.7 region at relative times of 400 \( \Delta t \). It is known that the viscosity of the molten matrix increases depending on the increase in the volume fraction of reinforcement [7,8].

As shown in Fig 1(a), the large particles are moved rapidly toward the ring outer periphery compared with small particles. This causes the sudden increase of viscosity of the molten matrix at the ring outer part of over 0.7 normalized thicknesses as shown in 200 \( \Delta t \) relative time. Consequently, the migration rate of small particles is lowered abruptly at the position and most of small particles remain in the ring inner region. Thus small particles with high density have a unique distribution profile as shown in Fig 1 at 300 \( \Delta t \) relative time. If the peak volume fraction of small particle is large, the density gradient of specimen should have attractive features. It is difficult that...
the large diameter particles can have high velocity in comparison with the small diameter particles, if both the differences in diameter and density are significantly large and small, respectively.

4. Physical properties of FGM with a unique density gradient

The large particles migrate toward the ring outer periphery faster than the small particle. Therefore, volume fraction of the large particles at the ring outer periphery is larger than that of the small particles, and the volume fraction of the large particles at the interior periphery is smaller than that of the small particles. If these two kinds of particles have different physical property each other, physical property of the FGM with a unique density gradient should show a unique variation as a function of normalized thickness. Here, the mean shear-modulus $\mu$ of specimen with the ring thickness, which has a unique density gradient as shown in Fig. 2, is calculated at each position of normalized thickness.

The model FGM is the combination of plaster as matrix, reinforcement as small particle and as large particle. The values of density as shown in the Fig. 2. Therefore, we can expect the fabrication of FGM, which have the highest strength at outer ring periphery, by a combination of particles with different size. This is an important advantage of the FGM fabricated by two kinds of particles compared with usual FGM fabricated by one kind of particle.
5. Conclusion
The research paper dealt with FGM particulate distributions of the two kinds of solid spherical particles fabricated by centrifugal force and analyzed using mathematical equations. The simulation showed that the relative motion of large particles is higher than that of smaller particulates in a molten matrix. The large particles can have higher migration rates compared with small particles, if the difference in diameter is significantly large. Thus, large particles migrate preferentially in a typical condition and prevent the movement of small. The phenomenon results in unique density gradation and one can obtain FGM rings with some kind of designed density gradients. The centrifugal infiltration process presented in the paper has the potential to become a practical guide to fabrication process for FGM.

References
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Design of Clamping Apparatuses for Testing Composition of Composite Wind Turbine Blades
FM. Liu, J H Wu, Y C Tseng, J S Wang
146
Development of Complex Hydrides for Various Energy Applications
Haiwen Li, K. Ikoda, T. Sato, M. Matsumo, S Orimo
148
Blurred Problem of Gel-Coating Surface of SCRIMP-GFRP
Hua Jeng Lin, CI Liao, CJ Tsai
150
Development of Studies on Mechanical Performance of Large-Deformation Concrete
Peng Liu, Ziqing Wan, Wensong Zhou
152
A Rheological Model of an Epoxy Resin System Used In Processing Wind Turbine Blades
Zhaozong Liu, Chaoyi Peng, Ziyu Xiao, Jingchun Zeng
154
Corrosion Detection in Pipe based on Correlation Coefficients
Hongwei Ma, Wenwei Zhang
156
A novel multi-measurand fibre-optic sensor
R. S Mahendran, V R Machavaram, L Wang, S N Kulkarni, M Paget and G F Fernando
158
Hot Embossing of Open Channel Polymer ESI-MS Chip Using Lasermachined and Electroformed Tools
Sana Mahbub, Pio Jovenet, Igor SBARSKI, Matthew Solomon
160
Self-Sensing Composites: Cure Monitoring and Damage Detection
Shoaib A. Malik, Liwei Wang, Venkata R. Machavaram and Gerard F Fernando
162
Correlation, silica content and enamel fissure properties
Philomena Chukwu and Marcela Muntean
165
Investigation of Physical Properties of Functionally Gradient Material using Centrifugal force
167
A Study on Failure Load Prediction of Single Lap Bonded Joint of Carbon Composite and Aluminium
Khanh Hung Nguyen, Jin-Hwe Kweon
169
Development of Post-Processor for 5-Axis Machining with Constant Feedrate
J Y Oh, J D Hwang, S Y Jung, YG Jung
171
Mechanical Material Properties of Long Glass Fiber Reinforced Plastic Foams Including Matrix Poly-Propylene
Shingo Okamoto, Y Fukuba, I Hanma, S Gasami, T Miyachi, T Tochioka, M Kando, Junich Ogawa
173
Dispersion of platelets Via Coarse-grained computer Simulations
R.B. Pandey, B.L. Farmer
175
Creep behaviour of composites produced from waste paper and plastic
Aaron James and Igor Sbarski
177
In-Line Compounding Of Long Fibre Reinforced Plastics and Injection or Compression Molding
Daniel Schwendsheim
179
The Simple Method For Fabricating Of Extrusion Billet Of Aluminium Alloy And Its Osmication
Sung Yong Shin, Dae Hwan Kim, Jian Qiong Lin, Su Gun Lam
181
Towards the Nondestructive Evaluation of Structural Integrity Using Wireless Sensor Networks
Kumar V Singh, Greg J Sheddell
183
Synergy Between Rubber-Toughening and Silica Nanoparticles in FRC
Stephan Sprenger, Anthony J Kanloch, Ambrose C Taylor, Reza D Mohammed
187
Load Distribution Analysis of Composite Blade for Small Wind Turbine
Shen Jao Su
189
Uncooled Infrared Imaging Micro-Cantilever Pixel Bi-material Structure with Optical Readout
Bohua Sun
191
Rubber Composite: a Deformable Nano Finishing Tool for Viscoelastic Flow Finishing Process
Pytebhunarm B Tayor, J Ramlunarm, Karnal K. Kar
193
Investigation of physical properties of functionally gradient material using centrifugal force

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Abstract

The objective of the paper is to study the physical properties of Al/SiC functionally graded materials prepared by centrifugal casting. Two sizes of SiC particles are selected as reinforcements. In the process, SiC particles are mixed with Al alloy in advance, and they are cast into a mould turning at a given constant velocity. The particles are distributed homogeneously into the Al alloy matrix during solidification of the matrix due to the centrifugal force caused by the difference in density between the Al matrix and SiC particle.

Introduction

A functionally graded materials (FGM) is a relatively new class of composite material, consisting of two or more phases, which is fabricated with its composition and/or microstructure varying in some spatial direction[1]. FGMs are of practical interest because the gradation of the physical and/or the chemical properties can be controlled. Several methods have been proposed to obtain the gradient structure in composite materials. The centrifugal method, proposed by Fukui et al., is one of the most effective methods [2]. In this method, a centrifugal force is applied to a mixture of molten metal and reinforcement particle. The particles are arranged gradually along the radial direction (centrifugal direction) due to the density difference between the molten metal and reinforcement particle. In poor works, it was found that Al/SiC [3], Al/Alni [4] FGMs could be successfully fabricated by this method. The objective of this research is to investigate physical properties of Al/SiC FGM prepared by centrifugal casting.

Experimental

Al6061/SiC FGM alloy is chosen as the matrix and SiC is selected as the reinforcements in this work. To FGM, 2 kg of the precursor composite were melted and centrifuged using a furnace. Inside the chamber, there is space to mount a vertically positioned alumina crucible containing the precursor composite, centred within an induction heating coil, as well as a horizontal graphite mould material, equipped with a dedicated resistance heating system. The vacuum chamber allows the passage of a series of K-type thermocouples, used to monitor the melt temperature, as well as the mould and FGM temperatures. When the melt reaches the desired temperature, the induction coil is lowered and a torque corresponding to a pre-selected program is applied to the rotating arm, thus imposing the desired acceleration pattern to the ensemble. During rotation, which lasts for 90 s, the melt is forced from the crucible, and is conducted through a pouring hole into the mould, where it cools down and solidifies. The samples produced are cylindrical in shape, with 60 mm both in length and diameter. Optical micrographs were taken using an Olympus metallurgical microscope (reflection type), fitted with a camera. The magnification used is 200.

Table 1 Chemical Compositions of Al6061 (wt %)

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>Si</th>
<th>Mg</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight %</td>
<td>97</td>
<td>7</td>
<td>0.28</td>
<td>2</td>
</tr>
</tbody>
</table>

Results and discussion

Typical microstructures of the specimens fabricated by the centrifugal method as shown in the Fig 1. The wt. % of the SiC particles is 10 %. A larger reinforcement accumulates at outer side than centre of the specimen. This is due to the migration of the SiC particles, which are dark.

Fig 1 Microstructure of the Al6061/SiC FGM
The respective alloying element (Cu and Mg) retained in the Al 6061/SiC ingots was determined by the inductively plasma atomic emission method, using three randomly selected specimens from each ingot. This method involved Dissolving a known amount of specimen in HNO₃, Atomizing the solution into a plasma, and Analyzing the plasma in the inductively coupled plasma spectrometer, which detects the wavelength of the alloying element.

The results from the inductively coupled plasma spectrometer showed that the retained alloying elements in the Al6061/SiC FGM ingots are given in the Table 2

<table>
<thead>
<tr>
<th>Distance in mm</th>
<th>Element</th>
<th>Al</th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>97.7</td>
<td>0.3</td>
<td>0.18</td>
<td>0.92</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>0.5-10</td>
<td>97.5</td>
<td>0.35</td>
<td>0.21</td>
<td>0.98</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>10-15</td>
<td>97.6</td>
<td>0.45</td>
<td>0.26</td>
<td>0.99</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>15-20</td>
<td>96.6</td>
<td>0.59</td>
<td>0.28</td>
<td>1.01</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>20-25</td>
<td>95.6</td>
<td>0.72</td>
<td>0.32</td>
<td>1.12</td>
<td>2.23</td>
<td></td>
</tr>
<tr>
<td>25-30</td>
<td>95.2</td>
<td>0.75</td>
<td>0.36</td>
<td>1.15</td>
<td>2.51</td>
<td></td>
</tr>
</tbody>
</table>

Quantitative assessment of SiC particulates in the MMCs/FGM specimens taken from the respective 5 mm thick discs (distance from the base of ingot), was carried using the chemical dissolution method [5] This involved weighing the FGM specimens, dissolving the specimens in hydrochloric acid and filtering to isolate the SiC particulates. The particulates were then dried and the weight % of SiC particulates was determined. The results of quantitative assessment of the SiC particulates were graphically plotted as a function of distance from the base for two FGMs as shown in the Fig 5. The results revealed an increasing trend in the amount of SiC with an increase in the distance from the base for two FGM ingots.

The density measurements were performed on polished specimens to quantify the density of the FGM. These measurements were carried out in accordance with Archemedes principle. Distilled water was used as the immersion fluid.

The results of density measurement computation are shown graphically in Fig 2. The results showed an increase in density with an increase in distance from the base of the ingot for Al/SiC. Moreover, it might be noted that the average values clearly exhibited an increasing trend, although standard deviations for some of the density measurements were large.

The results of micro-hardness measurements are shown in Fig 3. The results revealed significantly different micro-hardness values at either ends of the three FGM ingots synthesized. For Al/SiC micro-hardness of the metallic matrix was found to increase as a function of distance from the base of the ingot.

Conclusion

An increase in the weight percentage of SiC particulates along the deposition direction led to a progressive increase in the porosity levels and matrix hardness for Al/SiC FGMs. Density results for the FGMs revealed a decreasing trend with increasing weight percentage of particulates and this is attributed to the increasing porosity levels. A reduction in CTE value for the high SiC end could be observed, as compared to that of the low SiC FGMs.

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INVESTIGATION OF PHYSICAL PROPERTIES OF
FUNCTIONALLY GRADED MATERIALS USING
CENTRIFUGAL FORCE

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ABSTRACT

Normal mode cylindrical electromagnetic wave propagation in the Ionosphere – Earth Wave guide
with a wavy floor surface is discussed Then normal mode Electromagnetic wave propagation in an
atmospheric duct wave guide with a wavy floor surface is explained Future scope of this article is
presented at the end

1 INTRODUCTION

A FGM is a relatively new class of composite
material, consisting of two or more phases, which
is fabricated with its composition and/or
microstructure varying in some spatial direction [1-
3]. FGMs are of practical interest because the
gradation of the physical and/or the chemical
properties can be controlled. Several methods have
been proposed to obtain the gradient structure in
composite materials. The centrifugal method,
proposed by Fukui et al., is one of the most
effective methods [4-8]. In this method, a
centrifugal force is applied to a mixture of molten
metal and reinforcement particle. The particles are
arranged gradually along the radial direction
(centrifugal direction) due to the density difference
between the molten metal and reinforcement
particles. In previous works, it was found that Al/SiC
[9], Al/AlN [10] FGMs could be successfully
fabricated by this method. The fabrication of the
FGMs made by the centrifugal method can be
classified into two categories based on the melting
point of the reinforcement particle [11,12]. If the
melting point is significantly higher than the
processing temperature, the reinforcement particle
remains solid in a liquid matrix. This method is
named as a centrifugal solid-particle method. On
the other hand, if the melting point of the
reinforcement particle is lower than the processing
temperature, centrifugal force can be applied
during the solidification both to the reinforcement
particle and to the matrix. This solidification is
equivalent to the production of in situ composites
using the crystallization phenomena, and this
method is, therefore, named as a centrifugal in situ
method. It is well known that the particle size
distribution as well as the volume fraction of
particles in particle-reinforced, or dispersion-
strengthened, composite material play an
important role in controlling its mechanical
properties. Therefore, a detailed knowledge of
particle size distributions is required to predict the
mechanical properties of the FGMs. In our
previous study [13], particle size distributions in
the Al/AlN FGMs made by the centrifugal in situ
method have been studied. It is also found that as
the G number becomes larger, the particle size at
the ring's outer region becomes smaller. Here the G
number is the ratio of centrifugal force to gravity.
In the case of the centrifugal method, it is known
that the temperature of the melt decreases from the
inner to the outer region of the ring [14,15]. The
larger cooling rate for larger G-number specimens
is found. Therefore, we have concluded that the
difference in the particle size distributions should
be caused by the cooling rate. The objective of this
research is to investigate physical properties of
Al/SiC FGM prepared by centrifugal casting.

2 EXPERIMENTAL STUDIES

Al6061/SiC FGM alloy is chosen as the matrix and
SiC is selected as the reinforcements in the present
work

| Table 1 Chemical Compositions of Al6061(wt. %) |
|---|---|---|---|---|---|
| Elément | Al | Si | Cu | Mg | Cr |
| Wight | 97.9 | 0.6 | 28 | 1.0 | 2.0 |
To produce the FGM, 2 kg of the precursor composite were melted and centrifuged using a furnace. This furnace possesses a vacuum chamber (vacuum pressure $P < 0.3$ Pa) located in the extremity of a rotating arm moving around a vertical axis. Inside the chamber there is space to mount a vertically positioned alumina crucible containing the precursor composite, centred within an induction heating coil, as well as a horizontal graphite mould material, equipped with a dedicated resistance heating system. The vacuum chamber allows the passage of a series of K-type thermocouples, used to monitor the melt temperature, as well as the mould and FGM temperatures. When the melt reaches the desired temperature, the induction coil is lowered and a torque corresponding to a pre-selected program is applied to the rotating arm, thus imposing the desired acceleration pattern to the ensemble. The resulting angular velocity is measured by a system working with eddy-currents induced in a detector by a magnet fixed in the rotating arm. During rotation, which lasts for 90 s, the melt is forced from the crucible, and is conducted through a pouring hole into the mould, where it cools down and solidifies. The samples produced are cylindrical in shape, with 60 mm both in length and diameter. The processing conditions for the centrifugally cast FGM composite can be found in Table 2.

<table>
<thead>
<tr>
<th>MOULD SPEED</th>
<th>600 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME TAKEN TO ACHIEVE MAXIMUM ACCELERATION</td>
<td>9 SECONDS</td>
</tr>
</tbody>
</table>

Specimens were removed from the metal mass by specimen cutter. Care was taken to prevent cold working of the metal, which can alter the microstructural and complicate interpretation of constituents. Dry and wet grinding was performed with abrasive belts. Abrasives used for grinding were silicon carbide emery belts. Mechanical polishing is performed in two stages, rough and finish polishing. For rough polishing, emery belts of 100, 200, 400, 600, and 1200 (0-emery paper) were rotated on 500–600 rpm. The abrasive dust was collected at bottom of the belt. In dry grinding care was taken so that the specimen was not overheated, which otherwise will affect the microstructure. Progressing from one grit size to the next, the specimen was turned through 90° and was cleaned with cloth saturated with a water-soluble ethanol. Polishing machine wheels used for both polishing stages consists of a medium-nap cloth, (washable cotton), a suspension of MgO size of 5 μm particles mixed in distilled water (50 g per 500 ml of H2O) was used on the wheel for smooth polishing. The specimens were rotated counter to the wheel direction. Finally, for finish polishing, a diamond paste (1 μm) was used on the wheel. The specimen was moved across the face of the wheel and rotated counter to wheel rotation to change the contact point between specimen and wheel. The polished specimen was rapidly transferred from the wheel to running tap water and gently rubbed with a cotton ball to remove fine abrasive. Then it was rinsed in alcohol and in a blast of warm clean air. Light scratches and cold-worked surface metal on the polished specimen was removed by light etching and light re-polishing.

3. RESULTS AND DISCUSSION
3.1 MICROSTRUCTURE

Typical microstructures of the specimens fabricated by the centrifugal method as shown in Fig. 1. The wt % of the SiC particles is 10%. A larger reinforcement accumulates at outer side than centre of the specimen. This is due to the migration of the SiC particles, which are dark.

| POURING TEMPERATURE | 750 °C |
| MOULD TEMPERATURE    | 450 °C |

The respective alloying element (Cu and Mg) retained in the Al 6061/SiC ingots was determined by the inductively plasma atomic emission method, using three randomly selected specimens from each ingot. This method involved...
a Dissolving a known amount of specimen in nitric acid, b Atomizing the solution into a plasma, and c Analyzing the plasma in the inductively coupled plasma spectrometer that detects the wavelength of the alloying elements. The results from the inductively coupled plasma spectrometer showed that the retained alloying elements in the Al6061/SiC FGM ingots are given in the Table 3.

3.4 Quantitative assessment of SiC particulates
Quantitative assessment of SiC particulates in the MMCs/FGM specimens taken from the respective 5 mm thick discs (distance from the base of ingot), was carried using the chemical dissolution method [16,17]. This involved weighing the FGM specimens dissolving the specimens in hydrochloric acid and filtering to isolate the SiC particulates. The particulates were then dried and the weight % of SiC particulates was determined.

The results of quantitative assessment of the SiC particulates were graphically plotted as a function of distance from the base for two FGMs as shown in the Fig. 2. The results revealed an increasing trend in the amount of SiC with an increase in the distance from the base for two FGM ingots (30 µm and 50 µm in size).

The results of density measurement computation are shown graphically in Fig. 3. The results showed a decrease in density with an increase in distance from the base of the ingot for Al/SiC. Moreover, it might be noted that the average values clearly exhibited a decreasing trend, although standard deviations for some of the density measurements were large.

3.6 Micro-hardness measurements
Micro-hardness of the FGM / MMCs specimens was determined using an automatic digital micro-hardness tester shown in the Figure 5. The measurements were made using:
- A pyramidal diamond indenter with a facing angle of 136°
- 25 gf indenting load and
- A load dwell time of 15 s

The indentations were made on the matrix material at areas which were free from any SiC particulates.

### Table 3: Chemical Compositions of AL6061 (wt. %)

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Al</th>
<th>Si</th>
<th>Cu</th>
<th>Mg</th>
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<td>0.21</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td>0.15-0.20</td>
<td>97</td>
<td>0.45</td>
<td>0.26</td>
<td>0.99</td>
<td>1.29</td>
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<td>0.25-0.30</td>
<td>96.2</td>
<td>0.59</td>
<td>0.28</td>
<td>1.01</td>
<td>1.92</td>
</tr>
<tr>
<td>0.35-0.40</td>
<td>95.6</td>
<td>0.72</td>
<td>0.32</td>
<td>1.12</td>
<td>2.23</td>
</tr>
<tr>
<td>0.45-0.50</td>
<td>95.2</td>
<td>0.75</td>
<td>0.36</td>
<td>1.15</td>
<td>2.51</td>
</tr>
</tbody>
</table>

Distilled water was used as the immersion fluid.

The results of density measurement computation are shown graphically in Fig. 3. The results showed a decrease in density with an increase in distance from the base of the ingot for Al/SiC. Moreover, it might be noted that the average values clearly exhibited a decreasing trend, although standard deviations for some of the density measurements were large.

3.5 Density measurements
The density measurements were performed on polished specimens to quantify the density of the FGM. These measurements were carried out in accordance with Archimedes principle [16,17].
The results of micro-hardness measurements are functionally graded materials, with 10 weight percentage of SiC particulates. An increase in the weight percentage of SiC particulates along the deposition direction led to a progressive increase in the porosity levels and matrix hardness for Al/SiC FGMs. Density results for the FGMs revealed a decreasing trend with increasing weight percentage of particulates and this is attributed to the increasing porosity levels. A reduction in CTE value for the high SiC end could be observed, as compared to that of the low SiC FGMs. Significantly different hardness values could be-

4. CONCLUSIONS
Gradient slurry disintegration and deposition technique can be successfully used to synthesize free standing, one dimensional, Al 6061 based bulk of particulates and this is attributed to the increasing porosity levels. A reduction in CTE value for the high SiC end could be observed, as compared to that of the low SiC FGMs. Significantly different hardness values could be-
S. References


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An attempt has been made to investigate the processing of Al/SiC functionally graded composites (FGC) by centrifugal technique and to investigate the wear behavior. Two sizes of SiC particles are selected as reinforcement for this study. In the process, SiC particles are mixed with Al alloy in advance, and they are cast into a mould turning at a given constant velocity. The particles are distributed into the Al alloy matrix during solidification of the matrix due to the centrifugal force caused by the difference in density between the Al matrix and SiC particle. In FGM metal–metal and metal–particle wear resistance increased with increasing distance from the centre of the specimen. Worn surface examination of the FGM revealed formation of iron rich transfer layer during metal–metal wear test. Abrasive wear progressed by grooving action of the abrasive grains. Abrasion resistance of the end FGM specimens decreased with the size of the particle. When compared to the centre of the specimen for both Al FGMs exhibited abrupt increase in abrasion rate above higher speed and loads.

1. INTRODUCTION
Functionally graded materials are a class of advanced engineering materials that are characterized by continuous or gradual variations in composition and microstructure across the material’s thickness. These variations result in a corresponding change in the material’s properties [1–2]. The gradients formed are intentionally introduced and are quantitatively controlled to optimize the material properties so as to meet specific performance and functional requirements in the various fields of engineering. Wear tests using pin-on-disc mode were carried out and the wear mechanisms were studied by SEM observations. The wear mechanisms were discussed based on the obtained results.

2. EXPERIMENTAL STUDIES
Al6061 alloy is chosen as the matrix and SiC is selected as the reinforcements in the present work. To prepare FGMs, 2 kg of the precursor composite were melted and centrifuged using a furnace. Inside the chamber there is space to mount a vertically positioned alumina crucible containing the precursor composite, centered within an induction heating coil, as well as a horizontal graphite mould material, equipped with a dedicated resistance heating system. The vacuum chamber allows the passage of
Development of functionally graded materials for space applications

a series of K-type thermocouples, used to monitor the melt temperature, as well as the mould and FGM temperatures. When the melt reaches the desired temperature, the induction coil is lowered and a torque corresponding to a pre-selected program is applied to the rotating arm, thus imposing the desired acceleration pattern to the ensemble. During rotation, which lasts for 90 s, the melt is forced from the crucible, and is conducted through a pouring hole into the mould, where it cools down and solidifies. The samples produced are cylindrical in shape, with 60 mm both in length and diameter. In the present study, pins of the Al FGM under investigation were machined to 6 mm in diameter and 15 mm in length from the ingots and three different specimens taken from three different places from the ingots as shown in the Fig 1. At each load level, volume losses from the surfaces of specimens were determined as functions of sliding distance, sliding velocity, and applied load. The volume loss was calculated from the differences in weight of the specimens measured before and after the tests to the nearest 0.1 mg using electronic balance. Worn surfaces and transfer layers were investigated with SEM micrographs.

3. RESULTS

Typical microstructures of the specimens fabricated by the centrifugal method as shown in the Fig 2. The wt % of the SiC particles is 10 %. A larger reinforcement accumulates at outer side than centre of the specimen. This is due to the migration of the SiC particles, which are dark. Weight loss of the FGM composites as a function of sliding distance obtained from dry sliding metal–metal wear tests are plotted in Fig 3 & 4.

3.1 Effect of sliding distance Fig 3 & 4 show the effect of sliding distance on the wear rate at applied loads of 10-50 N with sliding speed of 100-400. The wear rates of both 30 μm SiC particulate reinforced and 50 μm SiC particulate reinforced of all three specimens with the sliding distance, but that of centre of specimen alloy shows a drastic increase in wear rate, after the sliding distances of 2 km in all the cases.

![Fig. 2 Microstructure of the Al/SiC FGM](image-url)

![Fig. 3 Wear rate of FGM with 30 μm corundum particles, measured with a pin-on-disc apparatus of normal load 10 N at a) 100 rpm and b) 200 rpm](image-url)
3.2 Effect of load on the wear rate

85 The wear rate results were plotted against applied loads as shown in the different figures. For both 30 µm SiC reinforced and 50 µm SiC reinforced FGM (for three specimens taken from different location of FGM ingots) the wear rate increases linearly with applied load, and also this diagram shows that there is a sudden increase in the wear rate at a particular applied load, i.e., a transition phenomena. It is clear from the figure that the transition loads are increased with increasing reinforcement.

3.3 Effect of sliding speed on the wear rate

The steady state wear rate, when plotted against sliding velocity, again exhibited two different regimes for the first specimen and second specimen for both 30 µm and 50 µm SiC reinforced FGM. Below sliding velocity of 200 rpm, the first specimen and second specimen exhibited similar wear rates. At sliding velocities higher than 200 rpm, the first specimen and second specimen reinforced FGM show sever wear rate, on other hand reinforced composites exhibit steady wear rates whose magnitude is much lower than that of matrix alloy.

3.4 Effect of distance from the ingots on wear rate

The results revealed significantly different wear rate values at either ends of the two FGM ingots synthesized. For both FGM, wear rate of the metallic matrix was found to increase as a function of distance from the base of the ingot.

3.5 Effect of particle size on wear rate

The results shows the wear rate for 50 µm SiC particulate reinforced FGM higher wear rate for inner specimens but outer specimen shows better performance than 30 µm SiC particulate reinforced FGM due to higher particulate concentration.

3.6 Worn surface studies

Representative SEM micrographs of the worn surfaces of the specimens taken from two types FGM and three specimens taken from three different places such as centre of ingots (0-10), middle specimen (10-20) and extreme end (20-30mm) of the ingots are shown in Figs. 5-6.

For Al/SiC (30 µm size SiC particulate reinforced) FGM, SEM examination of the worn surfaces of the specimens taken from centre of the specimen, the middle specimen and the
The results of quantitative assessment of SiC revealed that the FGMs synthesized in the present study exhibited a continuous gradient of SiC along the deposition direction. It was observed that the extreme ends of the ingot revealed that the low SiC, medium SiC and rich SiC particulate were dominated by delamination wear, while the high SiC end was dominated by less delamination wear (Fig 5). At 100 μm magnification, the worn surface of specimen from the low SiC end was characterized by long ploughing lines that run parallel to the direction of sliding, as illustrated in Fig 5(c). Such features suggest abrasive wear during sliding against the steel counterface. Furthermore, upon closer examination, shallow craters and holes of varying sizes, as well as cracks perpendicular to the sliding direction were commonly observed throughout the worn surfaces, as seen in Fig 6(b). The presence of these cracks and formation of such holes and craters during sliding of the specimens had been associated with the process of delamination on several occasions by other researchers [3]. As recorded by Suh et al. [4], delamination is the propagation of cracks preferentially along the sliding direction, which gives rise to the detachment of wear debris in the form of sheets. For the case of the specimen from the high SiC of Al FGM, delamination wear was also observed to be the dominant wear mechanism. This was confirmed by the presence of abundant flake-like wear debris collected from the wear of high SiC.

For Al/SiC (30 μm size SiC particulate reinforced) FGM, the worn surface of the centre specimen (low SiC particulate) had features of long ploughing lines that were parallel to the sliding direction, thus confirming the presence of abrasive wear. Moreover, there were long, shallow craters found on the worn surface of the low SiC specimen and this is a feature of delamination wear. On the other hand, the high SiC end was dominated solely by adhesive wear as shown in Fig 6(c). This was evident from the high magnification examination, which shows a rough surface as a result of the plucking out of small particles of pm material via adhesive transfer to the counterface.

4. DISCUSSION
The results of quantitative assessment of SiC revealed that the FGMs synthesized in the present study exhibited a continuous gradient of SiC along the deposition direction. It was
also found that for all the FGMs, the overall amount of SiC incorporated in each FGM was typically less than the starting. This could be due to:

- The removal of the shrinkage cavity found at the top of all the FGMs
- The lower-than-critical stirrer velocity for maximum possible incorporation of particulates

Earlier studies conducted by other researchers have convincingly shown the existence and need of a critical velocity for maximum possible incorporation of reinforcement for composite formulations synthesized using the liquid-phase route [5,6]. Furthermore, results clearly reveal that of the two FGMs, the gradient SiC at the base of Al/SiC was shown. Thus SiC will tend to settle most quickly in the Al matrix as also supported by the results obtained using the Stokes equation (given chapter 4). The relatively highest Vp led to shorter settling time of the SiC, leading to the reverse gradient observed along the deposition direction for Al FGM. Secondly, the presence of alloying element such as Mg had been reported to decrease the viscosity of aluminum [7]. Hence, this would lead to an increase in sedimentation of SiC with increasing fluidity of the molten metal.

Clustering of SiC was also found to increase from the low SiC end to the high SiC end, for Al/30\(\mu\)m SiC and Al/50\(\mu\)m SiC ingots. This could be essentially due to the slow stirring condition (400 rpm) adopted in this present study. This can be attributed to the ability of Mg to wet SiC, thus assisting in the improvement of their distribution [8]. In addition, for FGM, Cu-rich phases were observed in the Al matrix and this can be attributed to the near-equilibrium nature of solidification conditions realized in the present study. The formation of Cu-rich phase can be attributed to the sequential events involving:

- A sluggish solidification front velocity achieved during primary processing of materials,
- Rejection of Cu ahead of the moving liquid–solid interface
- Subsequent solidification when the temperature of the remaining liquid reached eutectic temperature [9]

Wear decreasing with distance from the centre of the ingots was due to the formation of the reverse gradient of SiC along the deposition direction. The extreme ends of the FGM ingots synthesized in the present study exhibited significantly different wear rate values, which could be primarily attributed to the significant variation in the weight percentages of SiC. These results obtained were consistent with those reported by other researchers and with the principles established for the strengthening of the metallic matrices associated with SiC particulates [10-11]. The presence of stronger and stiffer SiC led to an increase in the constraint to the localized plastic deformation of the matrix during the wear test. Moreover, the significant difference in coefficient of thermal expansion between the matrix material and the SiC. Both of these effects led to the hardening of the metallic matrix and this had been shown to increase with the increasing presence of silicon carbide particulates [12].

The significant difference in hardness values obtained on the extreme ends of all the FGMs also indicated that different tribological responses could be expected. This was partly confirmed by the wear rate results, which revealed that different wear rates were realized) from specimens taken from the extreme ends of the three FGMs. The wear mechanisms observed could be generally described as Abrasive wear, Delamination wear and Adhesive wear.

It was found that either a combination of the above-mentioned mechanisms or a single wear mechanism was dominant for each end of the ingots. This increase in wear resistance could be attributed to the increased resistance to plastic shear deformation imparted by the
Development of functionally graded materials for space applications

presence of more SiC, as a large number of cracks must be nucleated before loose debris could form [13]
The increase in hardness of the specimen at the high SiC end (presence of more SiC), thus resulted in a decrease in the rate of plastic deformation and thus led to crack propagation at shallow depth and lower crack propagation rate [14]. The presence of more silicon carbide in the Al matrix did not show any positive influence on wear resistance, unlike for the case of the other two FGMs. This can primarily be attributed to FGM having the highest level of reinforcement among the two FGMs at their respective high SiC ends.

5. CONCLUSION

In FGM Metal-metal and metal-particle wear resistance increased with increasing distance from the centre of the specimen. Worn surface examination of the FGM revealed that formation of iron rich transfer layer during metal-metal wear test. Abrasive wear progressed by grooving action of the abrasive grains. Abrasion resistance of the end FGM specimens decreased with the size of the particle. When compared to the centre of the ingot for both 30 μm and 50 μm SiC reinforced Al FGMs exhibited abrupt increase in abrasion rate above higher speed and loads.

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