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The Effect of the Increase in Graphite Volumetric Percentage on the Strength and Hardness of Al-4 Weight Percent Mg-Graphite Composites

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In this study, the fabrication of an Al-4 wt.% Mg-graphite particle composite is described. Composites of Al-4 wt.% Mg alloys containing 1-10 volume percentages of graphite particles were prepared using the compocasting technique. A pitched-blade stirrer was used to stir the graphite particles in the semi-solid melt, and the slurry was then poured into a metallic mould to obtain the cast bars. The emphasis of the investigation was on the important features of the castings obtained by this method, specifically the distribution of graphite particles along the cast bars and porosities. Then we studied the effect of the addition of the graphite on the strength and hardness of these cast bars. The results show that both the tensile strength and the hardness decrease with the increase in graphite content.

Keywords graphite, metal-matrix composite, particle recovery, particulate metal-matrix composite, porosity content, tensile strength

1. Introduction

It is well-known that the combination of certain desired properties can be achieved by the development of different composite materials. Composites have a wide range of applications in the automotive, aerospace, and other industries.[1] After more than 30 years of active research, metal-matrix composites (MMCs) are beginning to make a significant contribution to industrial applications. The properties of two or more materials can be engineered into MMCs.[2] Interest in MMCs reinforced either with fibers or with particles is directed mainly toward the Al matrix system. The combinations of lightweight, low-cost, environmentally resistant, and useful mechanical properties have made Al well-suited for use as a matrix metal. Also, improvements in its strength and hardness can be induced by the addition of materials such as Ti and Fe, and also by the addition of some reinforcement particles like alumina and silicon carbide.[3]

Many techniques are available today with which to synthesize MMCs, such as solidification processes. The particulate MMCs have attracted more and more attention in industrial sectors due to the ease of supplying low-cost particulate reinforcements such as alumina and silicon carbide. The cheapest route for the solidification processing of composites is found in stir casting and compocasting.

In recent years, considerable work has been done on Al-graphite particle composites. This class of composites is attractive because of their superior properties such as low friction, improved wear resistance, and excellent antiseizing properties. Al-graphite composites have been developed for self-lubricating tribological applications.[4]

The present work is an attempt to study the particle recovery and porosity of Al-4 wt.% Mg-graphite cast bars that were synthesized by the compocasting technique. Also, the effect of particle and porosity contents on properties such as tensile strength and hardness also was investigated.

2. Experimental Work

2.1 Materials

Commercial Al of 99.85% purity and fine graphite particles were used for the fabrication of cast Al-graphite particle metal composites. The chemical composition of the Al is shown in Table 1. Mg was added to the molten Al in order to promote wettability between the graphite particles and the molten Al. It has been found that Mg is the most important wetting agent

Nomenclature

V_c	Volume of the sample
V_p	Volume of the porosity
W_c	Weight of the sample
W_m	Weight of the metal matrix alloy of aluminum and magnesium
W_g	Amount of graphite particles in the cast bar
W_{add}	Amount of graphite particles added to the melt
ρ_c	Density of the composite
ρ_g	Density of the graphite particles.
ρ_m	Density of the metal matrix alloy of aluminum and magnesium

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Table 1 The Chemical Composition of the Aluminum

Al	Fe	Si	Cu	Mn	Mg	Zn	Ti	B	Ni
99.85	0.08	0.04	0.0004	0.0009	0.0008	0.0032	0.0043	0.0003	0.0014

affecting the dispersion and recovery of graphite in Al and Al alloy castings.[5] The recommended amount of Mg to be added to molten Al was 4 wt.% of the alloy.[6]

2.2 Experimental Set-Up and Equipment

The schematic diagram of the experimental set-up for both stircasting and compocasting is shown in Fig. 1. The set-up consists of an electric furnace and the stirring arrangement. The electric furnace was designed and constructed to fabricate the cast bars needed for our investigation. The dimensions of the furnace were selected to permit the use of different sizes of graphite crucibles and different types of stirrers. The stirring rod, which is 10 mm in diameter, is introduced into the melt from a hole at the top surface of the furnace. The stirring rod is fitted to a motor having a speed range from 150-1200 rotations per minute (rpm). The motor of the stirrer was held rigidly over the furnace. The stirrer holder was designed in such a way that the stirrer could be inserted in the central axis of the crucible and at any desired elevation. The maximum temperature obtained from this furnace was 1200 °C. The set-up was connected with a control unit to monitor the temperature inside the furnace and also to determine the length of time that stirring would be required before we started the stirring process. A special K-type thermocouple was used to measure the temperature of the metal inside the crucible during melting. The thermocouple was covered with stainless steel in order to protect it from damage by the high temperature inside the furnace. The thermocouple was connected to a digital display to enable one to read the temperature of the molten Al.

2.3 Casting Procedure

The processing of Al-4 wt.% Mg-graphite composite has been achieved by placing about 900 g of pure Al in a graphite crucible. The graphite crucible was inserted inside an electric furnace. The furnace was heated to 850 °C, until the Al was completely melted. After the melting of the Al, the furnace was switched off to allow the temperature to decrease. The temperature of the melt was monitored by the K-type thermocouple, which was inserted inside the melt at a depth of about 10 to 15 mm from its surface. The desired quantity of Mg was 65 g, taking into consideration an estimated loss of 20% due to evaporation and burning. The Mg was wrapped in Al foil and was plunged into the melt, which was at a temperature between 710 and 740 °C, with the aid of a holder. The Mg lump was manually stirred inside the melt until it was completely melted in the molten Al. The surface of the melt was cleaned by being skimmed with a steel rule. The stirrer was inserted inside the furnace to preheat it before beginning the stirring stage. The stirrer was coated by a slurry of alumina powder in sodium silicate and was dried in air in order to prevent the dissolution of the stirrer material in the molten Al. When the temperature of the melt was about 638 °C, the stirrer was inserted into the melt and was vigorously agitated at a speed of 600 rpm. As the temperature of the melt reached 635 °C, the furnace was switched on in order to achieve a constant holding temperature of 635 °C.

Depending on the particle content desired in the composite, graphite wrapped in Al foil and preheated to 400 °C for 1 h was inserted inside the crucible. Stirring took place for 4 min after the addition of the graphite particles. If ≥ 4 volume percent (vol.%) of graphite particles was to be added, the graphite was added in two equal stages, and after each stage the graphite was stirred for 2 min. At the end of the stirring period, the metal inside the crucible was taken out of the furnace and was poured into a metallic mould. Then the mould was left to cool in air to room temperature. Finally, the mould was opened to obtain the cast bars.

Appropriate samples from the top and bottom of the cast bars were cut to an approximate height of 15 mm using a sawing machine. Then, each of these samples was divided into two parts, which were used to obtain particle content and porosity content.

2.4 Determining Particle Content and Porosity Content

2.4.1 Particle Content. To estimate the particle content, one of the sample's two parts was dissolved in diluted hydrochloric acid (concentration, 37%; and extra pure). The Al and Mg were dissolved in the acid, while the graphite particles were left behind. Then the solution was filtered using ashless filters with very fast filtration. The filter paper containing the graphite particles was placed in a ceramic crucible of known weight. The ceramic crucible with it contents was placed over the flame of a burner to burn the ashless filter, which had a negligible weight. At the end of the burning stage, the crucible containing the graphite particles was allowed to cool and then was weighed using an accurate digital balance. The difference in weight represents the weight of the graphite particles in the dissolved sample. The amounts of graphite found in the cast bars are less than the amount of graphite added at the beginning to the melt. As a result of the low density of the graphite, some of the graphite particles were attached to the oxide layer at the surface of the melt through the insertion of the Al foil containing the graphite particles. It would be difficult for the graphite particles that were attached to the oxide layer to be sucked into the vortex again. Therefore, due to the loss of these particles, the amount of graphite that was actually found in the cast composites was parameterized in terms of particle recovery. Particle recovery is the ratio of the wt.% of graphite particles in the sample to the number of graphite particles added to the melt at the beginning, which can be expressed as

$$\text{Particle Recovery } (\%) = (W_g / W_{add}) \times 100\% \qquad \text{(Eq 1)}$$

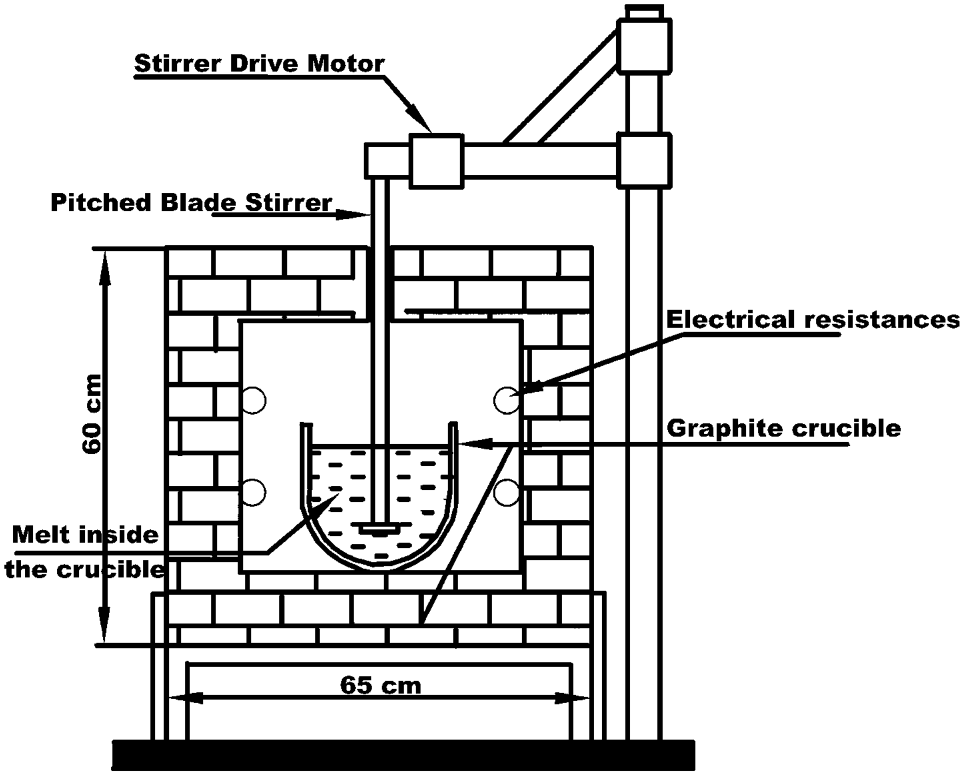

Fig. 1 Schematic diagram of the experimental set-up

2.4.2 Porosity Content. The second part of the sample was inserted in a vessel filled with water up to a known level. A small hole, or bridge, was opened from one side of the neck of the vessel in order to permit water to exit when a substance was immersed in the vessel. The vessel was filled with water to the level of the hole. Now, if a material sample is dipped inside the vessel, the volume of the water running out of the vessel through the hole will equal the volume of this sample. This volume of water can be measured by a graduated glass tube. By this method, the volume of the second part of the sample (V_c) was measured. Accordingly, the density of the composite ρ_c can be obtained from the following relation:

$$\rho_c = \frac{W_c}{V_c} = \frac{W_m + W_g}{V_m + V_g + V_p} \qquad \text{(Eq 2)}$$

The terms in Eq 2 can be rearranged to obtain the volume of porosity as:

$$V_p = W_m \left(\frac{1}{\rho_c} - \frac{1}{\rho_m}\right) + W_g \left(\frac{1}{\rho_c} - \frac{1}{\rho_g}\right) \qquad \text{(Eq 3)}$$

2.5 Properties Testing

2.5.1 Tensile Test. The tensile test was carried out by taking three specimens from the top, middle, and bottom of each cast bar. The tests were performed at ambient temperature. The test specimens were prepared using a Computer Numerical Control (CNC) turning machine. The dimensions of the tensile specimens were selected in accordance with ASTM specifications and standards. The dimensions of the test specimen are shown in Fig. 2. A WP 310 Universal Material 50 KN Tester was used to test the specimens. This type of testing machine can be used to test specimens that are smaller than those tested by other universal tensile testing machines.

2.5.2 Hardness Test. In order to measure the hardness of the cast bars, two samples from the top and bottom of each cast bar were prepared for the hardness test. Each sample was cut to a height of approximately 15 mm and was machined to a 35 mm diameter. Also, the faces of the samples were machined. Those two samples from the top and bottom of each cast bar were used later in the estimation of particle and porosity contents of the cast bar from which the samples were taken. Then the hardness was measured using scale B of the standard Rockwell hardness testing machine.

3. Results

3.1 Effect of Graphite Addition on Particle and Porosity Contents

Figure 3 shows the change in graphite recovery with the increasing in graphite addition (as vol. %) for samples from the top and bottom of each cast bar. It can be seen from this Fig. 3 that the amount of graphite recovered is greater at the bottom of the cast bars than at the top. However, the difference between the sample from the top and bottom of each cast bar is not high, with the maximum difference being about 12%. Figure 3 shows that graphite recovery decreases with increases in the vol.% of the graphite added to the melt.

The effect on porosity of the amount of graphite added to the melt is illustrated in Fig. 4 for the top and bottom samples.

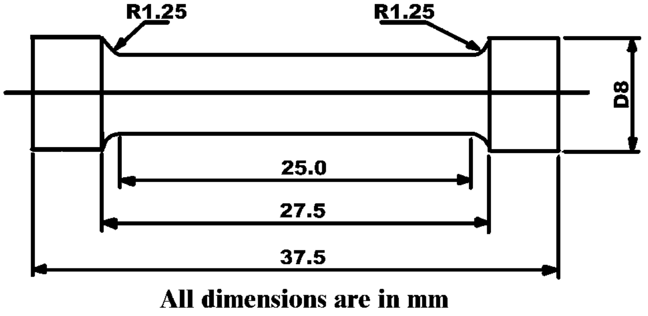

Fig. 2 Dimension of the tensile test specimen

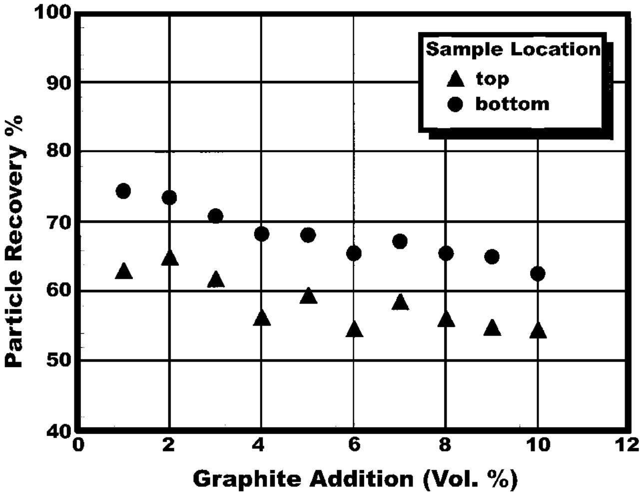

Fig. 3 The effect of graphite addition on graphite recovery for the top and bottom samples taken from the cast bars

This figure indicates that porosity increases with increasing additions of graphite in the cast bar. Also, this Fig. 4 shows that porosity is higher in the bottom samples than in the top samples.

3.2 Effect of Graphite Addition on Tensile Strength

Figure 5 shows the effect of graphite addition on the tensile strength of the three specimens taken from each cast bar. Three curves were plotted in this figure for these test specimens taken from the top, the middle, and the bottom of each cast bar. For specific graphite addition, the tensile strength increased from the bottom to the top of each cast bar. These curves indicate that the tensile strength decreased with an increase in the addition of graphite.

3.3 Effect of Graphite Addition on Hardness

The effect of graphite addition on the Rockwell hardness test (HRB) is shown in Fig. 6 for the top and bottom samples. Figure 6 shows that hardness decreases as the graphite addition increases. The hardness values are higher at the top than at the bottom of the cast bar.

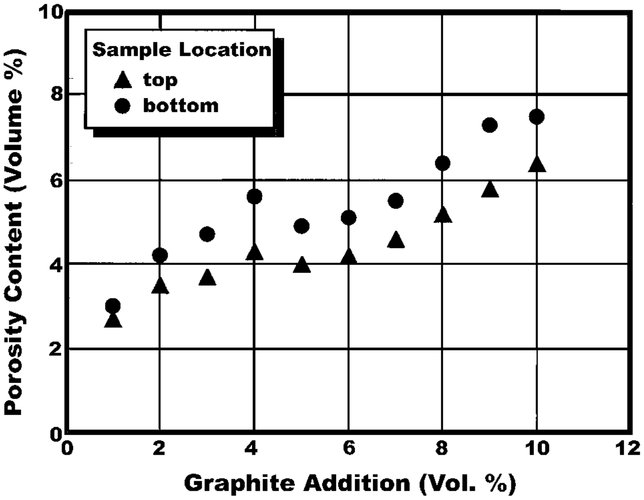

Fig. 4 The effect of graphite addition on the porosity content of samples taken from the top and bottom of the cast bars

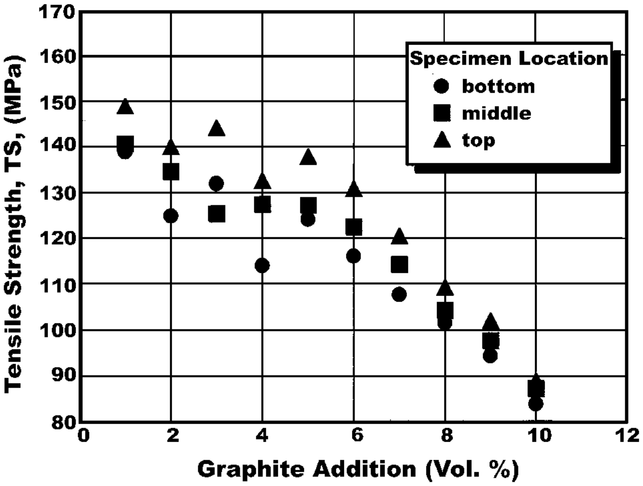

Fig. 5 The effect of graphite addition on the tensile strength of specimens taken from the top, middle, and bottom of the cast bars

4. Discussion

4.1 Effect of Graphite Addition on Particle Recovery and Porosity Content

The graphite particles are added by wrapping the graphite inside Al foil, and they should be added to the melt carefully in order to prevent their interaction or collision with the blades of the stirrer. This collision or interaction will hinder proper foil insertion into the melt and may help the foil to fall down on the melt surface. As a result of the foil falling down, some of the particles will become attached to the oxide layer at the melt surface and will not be allowed to disperse into the melt, decreasing the particle content in the cast bar. The possibility for the attachment of the graphite particles will be increased when the amount of graphite addition is increased, since the graphite is added in two installments. Also, another barrier in the insertion of the Al foil containing the graphite particles into the melt

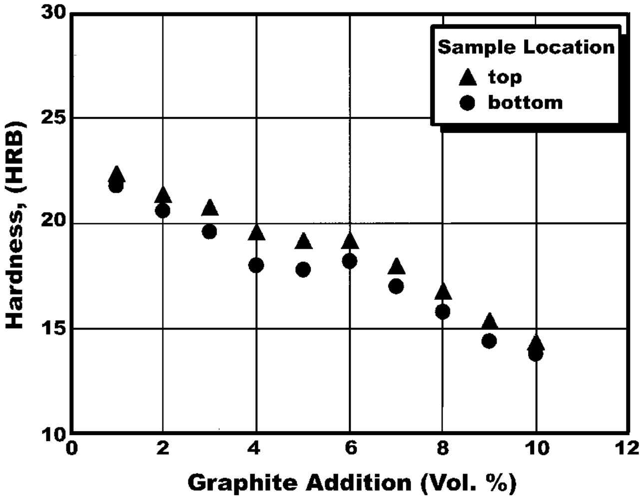

Fig. 6 The effect of graphite addition on Rockwell hardness (HRB) for samples taken from the top and bottom of the cast bars

is the primary solid phase of the melt. More pressure or force must be exerted in order to cross the surface oxide layer and the primary solid phase. This increased force may sometimes bend the foil and then cause it to fall on the melt surface, especially in the final insertion stages. All the above actions lead to a decrease in particle content as the amount of graphite added is increased, as can be observed from Fig. 3. When the amount of graphite is increased, the number of bubbles attached to these particles will increase. These combinations coalesce and float up faster, and some of them may become attached to surface layer at the melt surface. This process continues during stirring, leading to a decrease in the particle content in the castings.

The existence of the primary solid phase, when compocasting is used, enhances the viscosity of the melt. This will cause the graphite particles to collide with the primary solid phase, which will result in the more uniform distribution of these particles in the slurry. The small differences in graphite particle recovery and porosity content between the top and bottom of the cast bars are a result of this collision, especially at the bottom of the semi-solid melt.

The mixing of the poor wettable graphite particles in the Al melt causes the attachment of air bubbles to graphite particles. It is energetically favorable to replace the particle-liquid interface by the lower energy particle-vapor interface. It can be observed from Fig. 4 that the increase in particle content will cause an increase in the porosities. The blade stirrer makes a strong vortex, which sucks more bubbles into the melt, resulting in the greater dissolution of gases and thereby increasing the level of porosities in the castings. However, the increase in the viscosity of the melt, when the compocasting process is used, will prevent the air bubbles from floating. Also, the solidification time is relatively short, and some of the combined bubble-particle will be hindered from floating and will remain inside the solidified casting.

4.2 Effect of Graphite Addition on Tensile Strength

During the stirring of the slurry, a vortex is formed that sucks air bubbles into the slurry, as has been mentioned earlier, and these bubbles may become attached to clusters of particles. It was observed earlier[7] that cast composites fabricated by the compocasting technique have a high level of porosity along with an increased tendency for particle clustering. Around these pores, a weakened zone will be formed. The weakening effect of these zones will cause the observed reduction in tensile strength.

4.3 Effect of Graphite Addition on Rockwell Hardness

The indentation formed by the hardness test indenter will cause a plastic flow of the material because of the compression action of the indenter. This plastic flow occurs under the restraint of the surrounding material near the indentation zone. If the pores are available in the indentation zone, then this will give the deformed material the chance to flow into these pores without any restraint. Therefore, the presence of these pores results in a lowering of the hardness, and if the volume of the pores increases, an accompanying decrease in hardness will result and the material will appear to be softer. It was mentioned earlier that an increase in the graphite content will increase porosity (as shown in Fig. 4). So, it can be said that the addition of graphite will cause a decrease in the hardness. However, the changes in hardness values are not great. The diameter of the steel ball indenter used in the Rockwell hardness test was 1/16 in. (1.588 mm), which is large compared to the size of the pores. Therefore, this size of indenter causes plastic deformation with a volume larger than the size of the pores, and this difference in the volume will result in a small decrease in hardness.

Furthermore, the increase in the graphite addition will assist the plastic flow of the matrix metal, which will cause a reduction in its resistance to indentation that will lead to a decrease in hardness. Graphite is composed of layers, and within these layers strong bonds occur while weak bonds are connecting these layers with each other. As a consequence of these weak interplanar bonds, graphite is easily sheared. In addition to the lubricative nature of graphite to assist the plastic flow, this shearing appears to occur under the compression action of the indenter.

5. Conclusions

The following are the main conclusions that emerged from the present investigation:

1) The compocasting technique can produce a uniform distribution of graphite particles along the height of the cast bars. This is evident through the small difference between top and bottom recoveries. The primary solid phase hinders the flotation of graphite particles toward the top of melt.
2) The porosities of the obtained cast bars were almost homogeneously distributed in the cast bars. However, the level of these porosities is relatively high due the strong vortex of the pitched blade stirrer, which sucks more bubbles into the melt, and enhances the dissolution of gases.
3) Tensile strength and Rockwell hardness (HRB) were found to decrease with the increase in graphite content due to the increase in porosities and to the structure and lubricative nature of the graphite particles.

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References

1. A. Berghezan: *Basic Design Concepts and Specific Methods for the Fabrication of Metal-Matrix Composite Materials*, Applied Science Publishers LTD, London, 1978.
2. P.K. Rohatgi: "Cast Metal-Matrix Composites" in *ASM Handbook*, ASM International, Materials Park, OH, 1992, pp. 840-52.
3. M.K. Surapa and P.K. Rohatgi: "Preparation and Properties of Cast Aluminum-Ceramic Particle Composites," *J. Mater. Sci.*, 1981, *16*, pp. 983-93.
4. P.K. Rohatgi, S. Ray, and Y. Liu: "Tribological Properties of Metal Matrix-Graphite Particle Composites," *Int. Mater. Rev.*, 1992, *37*(3), pp. 129-49.
5. B.P. Krishnan, M.K. Surappa, and P.K. Rohatgi: "The UPAL Process: A Direct Method of Preparing Cast Aluminum Alloy-Graphite Particle Composite," *J. Mater. Sci.*, 1981, *16*, pp. 1209-16.
6. J.A. Al-Jarrah: "Synthesis and Tribological Characterization of Aluminum Base Composites," Ph.D.Thesis, University of Roorkee, Roorkee, India, 1998.
7. P.K. Gosh, and S. Ray: "Effect of Porosity and Alumina Content on the High Temperature Mechanical Properties of Compocast Aluminum Particulate Composites," *J. Mater. Sci.*, 1987, *22*, pp. 4077-81.