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Development and Thermal Property Evaluation of Aluminum Alloy Reinforced with Nano-ZrO_2 Metal Matrix Composites (NMMCs) For Automotive Applications

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Abstract

The improved mechanical properties such as high hardness, high specific strength and good thermal properties of aluminum alloy based metal matrix composites operating at elevated temperature has proved its capability to match stringent applications in the field of aerospace and automotive applications. The present investigation aims at reinforcing nano-sized ZrO_2 particles in the aluminum alloy (LM 13) developed via stir-cast route using chilling technique which remains an attractive choice among all other solidification routes, as chills promotes directional solidification and influence in the production of sound casting. The size of particulates dispersed varies from 70 to 100nm and the amount of addition varies from 3 to 15wt% in steps of 3%. The Microstructural analysis of the resulting nanocomposites reveals the uniform distribution of the reinforcement in the matrix alloy with significant grain refinement obtained due to the presence of nano-sized reinforcement. Thermal property of developed NMMCs were characterized via thermal conductivity using guarded comparative longitudinal heat flow techniquein accordance with ASTM-E1225-04 standards. The resulting NMMCs find its suitability in the production of automotive components such as piston, connecting rod, cylinder etc.

Keywords: Nano-ZrO_2; vortex route; chilling; NMMC; microstructure; thermal conductivity.

1. Introduction

Aluminum alloys based composites that freeze over a range of temperature experience difficulty in feeding as the solidification progress [1, 2]. Porosity results in pasty type of solidification which commonly occurs in long range freezing alloys that can be effectively treated by judicious location of chills. Chills transfers heat at faster rates and promotes direction solidification. There are several investigations on the influence of chills on the solidification and soundness of long freezing range alloy castings [3-10]. The analysis related to the non-metallic chilled NMMCs reinforced with nano-sized ZrO_2 particulates is undertaken because from the examination of literature that no data available on silicon carbide (non-metallic) chilled Al based NMMCs. In the last twenty years, metal matrix nanocomposites have encountered a massive development and Particulate-reinforced nanocomposites have been extensively employed in the automotive industry for their capability to withstand high temperature and pressure conditions. Aluminum alloy reinforced with ceramic particulates exhibits best tailored properties of two different materials, such as ductility and toughness of the aluminum matrix and the high modulus and strength of ceramic reinforcement and near isotropic properties. These materials are of special interest because of their ease of fabrications at relatively low cost. Use of nano-sized particulates as reinforcement in metallic materials has inspired considerable research interest in recent years because of the potential development of novel composites with unique mechanical and physical properties.

1. 1 Volumetric Heat Capacity (VHC) of Chill

The rate at which the heat is extracted from the solidifying molten metal in the mould will depends on the size and properties of chill material. The chill efficiency can be evaluated using the relation as given below.

$$VHC = V \times C_p \times \rho$$

Where V is the volume of the chill, C_p is the specific heat of the chill material, and ρ is the density of the chill material. During solidification with chill in the mold, the heat transfer takes place through the metal-chill interface during initial stages of solidification. Subsequently, an air gap forms between the casting and the chill face due to dissimilar thermal behavior of the chill and the surface of the thin layer of the solidified metal. This air gap results in temporarily delaying the heat transfer. In the final stages, the heat transfer takes place again in direct contact with casting and the chill surface [11]. The thermal properties of silicon carbide chill are shown in the Table 1.

Table 1. Volumetric heat capacity of silicon carbide Chill

Chill material	Density g/cc	Specific heat J/Kg K	Thermal conductivity W/mK	VHC for 35mm chill thick
Silicon carbide	2. 36	1. 095	0. 031	214. 88

Experimental Procedure

The chemical composition of the aluminum alloy used as the matrix is given in Table 2. In the present investigation, nano-sized ZrO_2 particulates were dispersed in Aluminum alloy by stir-cast route. The size of the nano-ZrO_2 particulates dispersed varies from 70 to 100 nm and the amount of addition varies from 3 to 15 Wt. % in steps of 3%. The synthesis of monolithic and NMMCs containing five different weight percentage of ZrO_2 involved heating of Al alloy in a graphite crucible up to 750^oC to which the preheated reinforcement (up to 600^oC) was added and stirred well by an mechanical impeller rotated at 400 rpm to create vortex in order to get uniform distribution of the reinforcement in the liquid melt. After the complete injection of the reinforcement in the molten metal, it was then poured into dry sand mould containing silicon carbide as end chill. This was allowed to solidify under the influence of end chill thus promoting directional solidification in order to produce sound casting. The mould produced cylindrical casting of dimension Φ50 mm X 50mm were prepared according to American Foundrymen Society (AFS) using silica sand with 5% bentonite as binder and 5% moisture and dried in an air furnace. The silicon carbide chill dimension remained Φ 55mmX35mm.

Properties of reinforcement (ZrO_2) are as follows. Density: 8.1 gm/cm^3, melting point: 1860^oC, UTS: 425 MPa, VHN: 150, young's modulus:98GPa (ZrO_2 is supplied by Nano Structured and Amorphous Materials, Inc., USA).

Table 2 Chemical Composition of Matrix alloy

Elements	Zn	Mg	Si	Ni	Fe	Mn	Al
Wt. %	0. 5	1. 4	12	1. 5	1. 0	0. 5	Bal

3 Specimen Selection and Testing Procedure

All the test specimens are prepared from the casting choosing near to chill end. Microstructural characterization studies were conducted on polished NMMC and monolithic matrix alloy specimens using NIKHON-Metallurgical microscope LV150-Japan make with clemax image analyzer to investigate morphological characteristics of grains, reinforcement distribution and interfacial integrity between the matrix and reinforcement. The thermal capability of developed NMMCs and monolithic matrix alloy are characterized for thermal property via thermal conductivity by using Longitudinal Heat Flow Technique in accordance with ASTM Standard E1225-04, which is related to the measurement of thermal conductivity of solids. An experimental set-up was established in heat and mass transfer lab and its schematic diagram of the experimental set up is as shown in the Fig. 3 &4. The test specimen is mounted in-between the two standard pure aluminum bar as shown in the Fig.1. The top bar represents the heat source and heater tape is wrapped tightly as shown in the Fig. 3. Care is taken to wrap the heater tape with asbestos tape & plaster of paris to prevent heat losses diametrically. Finally round of asbestos thread is wrapped tightly over the asbestos tape for better insulation (secondary insulation) as shown in the Fig.

4. Some dead weight is also placed on top of heating bar to establish close contacts between each other. A heat sink is placed at the bottom of setup to ensure one dimensional heat flow from top to bottom with 12 volts fan used to circulate air through the fins of heat sink. All electrical connections are made as per the circuit diagram shown in the Fig. 2. The power source is switched on and a constant voltage of 113Volts is maintained through dimmerstat. Temperature reading are recorded at regular intervals of 5 minutes till steady state is reached. The above same procedure is repeated by replacing the central matrix Al-alloy bar with the NMMCs containing varying wt.% of nano-ZrO_2 (3wt. % to 15% insteps of 3%) and the corresponding temperature readings are recorded. The thermal conductivity of the matrix Al-alloy bar is calculated using Fourier relations as given below.

$$Q = k\,A\,dT/dx$$

Where
k = Thermal conductivity of the material
A = Cross section area across through which heat is transferred
dT = Difference in temperature along the direction of heat flow
dx = The length between the 2 points where temperature is measured
Q = Rate of heat transferred

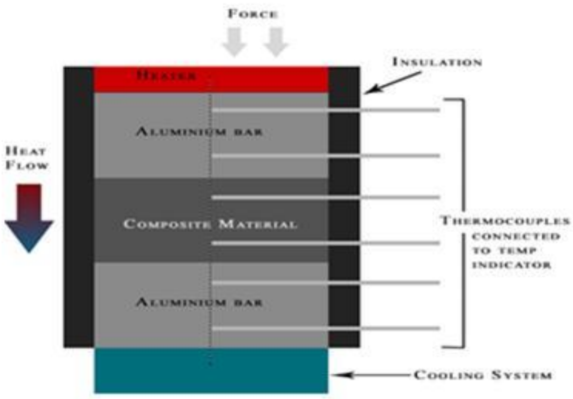

Fig. 1 Schematic diagram of Guarded Comparative longitudinal heat flow technique

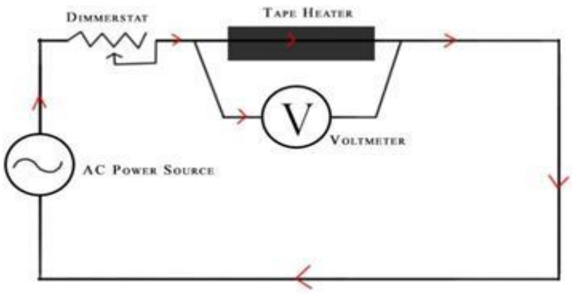

Fig. 2 Circuit diagram of the setup

Fig. 3 The top and bottom being pure Al bar and middle bar being NMMCs with thermocouple inserts

Fig. 4 Setup with primary & secondary insulations

4 Results and Discussion

4. 1. Synthesis of NMMCs

Synthesis of NMMCs and monolithic matrix alloy were successfully accomplished by judicious implementation of parameters such as preheating of reinforcement, effective stirring and chilling technique used to promoting directional solidification to realize sound casting by preventing microprosity, segregation or agglomeration of reinforcement. Thus indicating the feasibility of sand casting process as a potential fabrication technique for nano-ZrO_2composists.

4. 2. Microstructural Characterizations

Microstructural characteristics of NMMCs are discussed in terms of distribution of reinforcement and reinforcement matrix interfacial integrity. Microstructural studies conducted on NMMCs exhibits uniform distribution of reinforcement (Fig. 5 to 7), good reinforcement matrix interfacial integrity. This can be primarily attributed to the parameters such as pre-heat treatment of the reinforcement before transferring into molten matrix alloy influencing good wetting and enhances good bond strength. Mechanical agitation (stirring) enhances physical wetting between the liquid aluminum matrix and nano-ZrO_2 particles by overcoming surface energy barriers. However the results of microstructural characterization of NMMCs did not reveal presence of any microporosity or shrinkage cavity and this can be attributed to the effective feeding of metal to the regions of last solidifying liquid by establishing steep temperature and solidification gradient to promote directional solidification throughout the solidification process by the implementation of chills. Metallography studies of the samples revealed that, the matrix is completely refined in case of NMMCs can primarily be attributed to capability of nano-ZrO_2 particulates to nucleate Al grains during solidification and restricted growth of recrystallized Al grains because of presence of nano-scaled reinforcement.

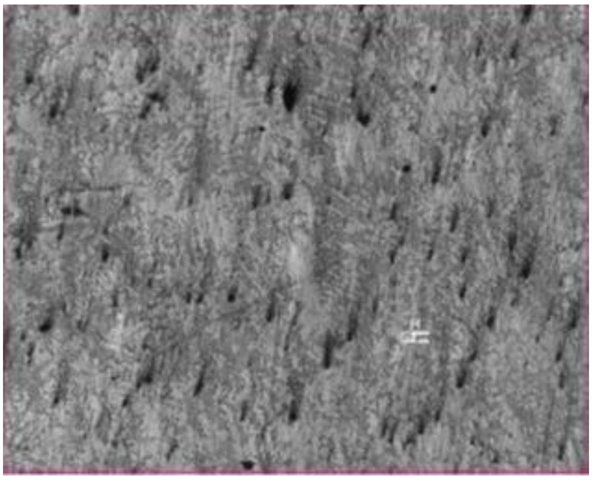

Fig. 5 Optical microstructure of NMMCs containing 9 wt. % of reinforcement at 200X

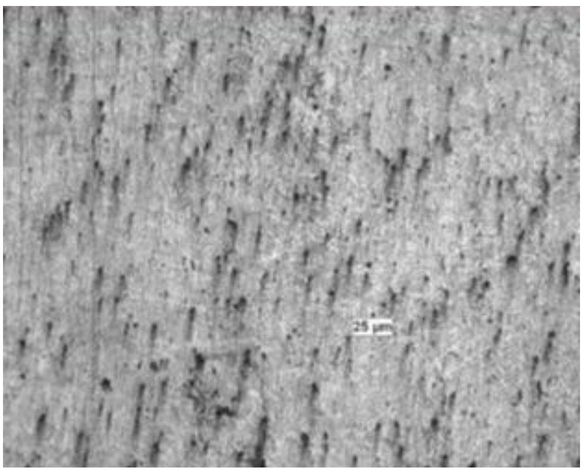

Fig. 6 Optical microstructure of NMMCs containing 15 wt. % of reinforcement at 200X

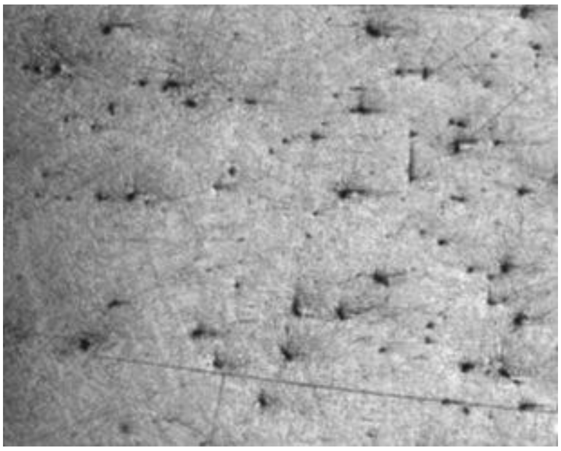

Fig. 7 Optical microstructure of NMMCs containing 6 wt. % of reinforcement at 200X

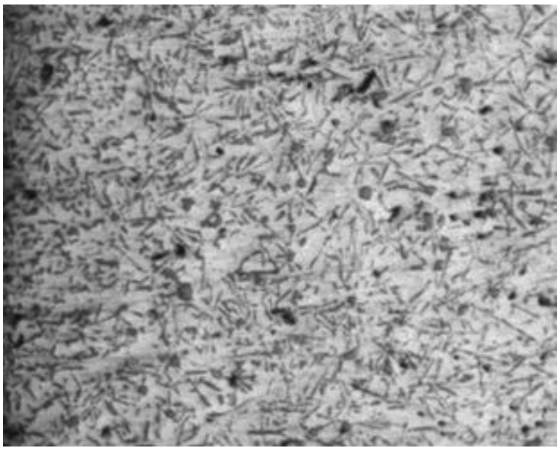

Fig. 8 Optical microstructure of matrix alloy (LM 13) at 200X

4. 3. Thermal conductivity:

The thermal property investigation via thermal conductivity of extruded NMMCs and matrix alloy are obtained by guarded comparative longitudinal heat flow technique are as shown in the Table 3. It is obseved from the results that the increase in concentration of nano-sized ZrO_2 in the matrix alloy has a significant effect on thermal property. The thermal conductivity of the NMMCs exhibits decrease in trend with increase in ZrO_2 concentration, this can be primarily attributed to the presence nano-sized ZrO_2 particle and its unniform distribution in the aluminum matrix and also the good insulating properties of hard ceramic particles. Higher the reinforcement concentration leads to increase in phonon scattering which will intern reduces the thermal conductivity [12]. The NMMCs containing 3 wt. % of ZrO_2 has registered is maximum value of thermal conductivity in the order of 144. 37 W/mK and the least value of thermal conductivity is registered for NMMC containing 15 wt. % ZrO_2 in the order of 115. 02 W/mK. Hence in order suit its application to thermal fields in perticular to heat engines of automotive sectors operating at elivated temperatures, which will cause lower heat losses from the engine and thus enhacing its thermal efficency of the engine. It is also important to have the knowledge of material design in perticular to design of engine components which has to restore some amount of heat inside the engine that could be ultilized in enhancing the thermal efficiency of engine, thus increasing the fuel efficiency.

Table 3 Thermal conductivity of NMMCs and matrix alloy

SL. NO	Material	Thermal conductivity (W/mK)
1	3 wt. % ZrO_2	144. 37
2	6 wt. % ZrO_2	137. 27
3	9 wt. % ZrO_2	128. 82
4	12 wt. % ZrO_2	124. 97
5	15wt. % ZrO_2	115. 02
6	Matrix alloy	158. 55

5. Conclusions

Synthesis of NMMCs via stir-cast route associated with chilling technique was successfully achieved. The Microstructural studies revealed more uniform distribution of reinforcement in the matrix alloy with good interface integrity between the reinforcement and the matrix alloy. Significant grain refinement attributing to the capability of nano-ZrO_2 particulates to nucleate Al grains during solidification process. The thermal conductivity of NMMCs decreases with increase in degree of reinforcement concentration in the matrix alloy. Thus indicating its feasibility to reduce heat losses and enhancing thermal efficiency of the engine with extension of its application as a candidate material in the manufacture of engine components.

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