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Effect of heat transfer on strength and fracture behavior of Al/Al_2SiO_5/C hybrid MMCs

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This paper describes research on Aluminum based Metal Matrix Composites (MMCs) reinforced with Al_2SiO_5(Kaolinite)/C(carbon) particulates cast in moulds using high rate heat transfer techniques during solidification using metallic and non metallic chills. Chilled composites are obtained by dispersing Al_2SiO_5/C particles in molten aluminum alloy above the liquidus temperature, the size of both the particles dispersed being between 50 μm to 100μm. The dispersoid being added ranges from Al_2SiO_5-3 vol.%/C-3 vol.%, Al_2SiO_5-6 vol.%/C-3 vol.%, Al2SiO5-9 vol.%/C-3 vol.% and Al_2SiO_5-12 vol.%/C-3 vol.% respectively. The resulting composites cast using chills were tested for their strength and fracture behavior. The effects of the various input parameters on strength and fracture behavior of the castings are discussed in detail in relation to their microstructure. These properties of the MMCs were found to improve with the rate of heat transfer during casting. The rate of heat transfer is in turn dependent on the properties of the chill material. After fracture testing, the material surfaces were examined using SEM and the fracture mechanisms were analyzed.

1. INTRODUCTION

In recent years there has been a great deal of interest in developing metal matrix composites (MMC) because of their unique mechanical properties such as light weight and high elastic modulus. The common fabrication routes of particulate reinforced MMCs include spray deposition, liquid metallurgy and powder metallurgy. Since expensive equipment is required and the processing routes are usually complex, the cost to produce MMCs by these methods is high, which has limited the applications of MMC materials. Presently, the bonding technique of hot-cold rolling process developed to fabricate particular reinforced MMCs involves complexities. Several other process used to produce discontinuous MMCs also include rheocasting, compocasting and squeeze casting. Many reports on the characterization of mechanical properties of discontinuous MMCs have been available. According to them, mechanical properties such as Youngs modulus and strength, have been improved about 50 ~ 100 % by incorporation of reinforcements. However, ductility has deteriorated remarkably with increasing content of reinforcements. There are many microstructural variables, such as the aging condition of the matrix alloy, the material used as reinforcement, the volume fraction and the size of the particulates, and each of these may effect the mechanical properties of the composite. An attempt made by S.C.V. Lim et al., reveal that, incorporation of SiC particulate as reinforcement into the matrix increases macro-hardness and elastic modulus but decreases ductility and coefficient of thermal expansion. Reinforcing an Al alloy with Al_2SiO_5/C particulates yields a composite that displays the superior mechanical properties of both the metal matrix and the dispersoid. For instance, the toughness and ductility of Al can be combined with the strength and hardness of the Al_2SiO_5/C particulates. On a weight-adjusted basis, many Al-based MMCs can outperform cast steel, Al, Mg and virtually any other reinforced metal or alloy in a wide variety of applications. Hence, it seems probable that such MMCs will replace conventional materials in many commercial and industrial applications in the near future.

2. EXPERIMENTAL PROCEDURE

2.1. Chemical Composition of MMCs

Chemical composition of the aluminum alloy used as the matrix is given in Table-1. In this investigation Al_2SiO_5/C particles of Al_2SiO_5-3 vol.%/C-3 vol.%, Al_2SiO_5-6 vol.%/C-3 vol.%, Al_2SiO5-9 vol.%/C-3 vol.% and Al_2SiO_5-12 vol.%/C-3 vol.% were dispersed in the matrix.

2.2 Chilled composite preparation procedure

The Al alloy is introduced into a specially designed bottom pouring composite melting furnace. After melting the charge at around 750^{o}C (heated in an inert atmosphere for 45 minutes at 700^{o}C), preheated Al_2SiO_5/C particles at 700^{o}C are introduced evenly into the molten metal by means of special feeding attachments. During this process, the molten metal is well agitated by a mechanical impeller specially to create vortex motion. The speed of the impeller is maintained at 760 rpm. The process of dispersing the particles is completed with in one minute. After the complete injection of the dispersoids, the molten metal is again stirred for few seconds. Later, at 740^{o}C, it is poured into a mould containing different types of end chills to vary the rate of heat transfer.

The moulds for the plate type of castings 225*150*25 mm (AFS standard) were prepared using silica sand with 5% bentonite as binder and 5% moisture and finally they were dried in an air furnace. The dispersoid treated Al alloy was poured directly into the mould at a pouring temperature of 740^{0}C, which was cooled from one end by a chill set in the mould. Ingots were cast employing different chills in order to study the effect of heat capacity of the chill on the strength, fracture behavior and microstructure of the composite developed. Length and breadth of the chill were kept constant at 170 and 35 mm respectively. Thus this method of preparing the composite by melt metallurgy technique in the vortex route produces Al/Al_2SiO_5/C chilled composite of consistent chemical analysis.

2.3 Specimen selection and preparation

The tensometer specimens for the strength tests were prepared according to American Foundrymen Society (AFS) standards and chevron notched specimens for fracture toughness tests (3 point bend method) were prepared according to ASTM E 399-1990.

To study the effect of chilling during solidification on the fracture behavior of the MMCs, the procedure was repeated with chills of the same shape and size made of copper, steel, cast iron and silicon carbide respectively.

3. TESTING PROCEDURE

3.1. Strength Test

Tension tests were performed using Instron tension testing machine on AFS standard tensometer specimens. Each test result was obtained from an average of at least three samples of the same location.

3.2. Microstructural Examination

Microscopic examination was conducted on all the fractured specimens using VG 9000 scanner as well as Neophot-21 metallurgical microscope. Various etchants were tried but dilute Kellers etchant proved to be the best and was therefore used. Photomicrographs of all the specimens before testing were taken to study their micro-constituents and the distribution of Al_2SiO_5/C particulates.

3.3 Fracture Toughness Test

Fracture toughness test were performed using a closed-loop INSTRON servo-hydraulic Material Testing System (MTS) in accordance with ASTM E 399-1990 standards. The method of testing involved the 3-point bend testing of notched (chevron type) specimens, which had been pre-cracked by fatigue using reversed push-pull loads. The validity of this method depends on the establishment of a steep crack condition at the tip of the crack in a specimen of adequate size. All these conditions were fulfilled in this experiment.

4. RESULTS AND DISCUSSION

In the present investigation, of all the chills, copper chill was found to be the most effective because of its high VHC. Dispersoid content combination from 6 vol.% to 12 vol% was found to increase the mechanical properties (strength and fracture toughness) and therefore Al_2SiO_5-9vol.%/C-3 vol.% is considered as the optimum limit. Hence the present discussion is mainly based on chilled Al/Al_2SiO_5/C composite with 12 vol.% dispersoid combination chilled using copper chill. Carbon content in all the MMCs is limited to 3 vol.% since it deteriorates the mechanical properties if added in excess, where as Al_2SiO_5 content in MMCs is varied from 3 to 12 vol.%.

The Microstructures reveal that the Al_2SiO_5/C particulates are uniformly dispersed in the aluminum matrix. Microstructural studies also reveal that, the most unique feature of rate heat transfer rate (effect of chilling) during solidification of the composite in this investigation is the apparent pushing of the solid-liquid interface during solidification leaving only the dispersoids in the matrix. This may be one of the main reasons for increase of strength and fracture toughness of the composite developed.

The mechanisms, which control the variation of fracture toughness of chilled Al_2SiO_5/C composites, are dependant on both microstructure and strain range. The possible micro-mechanisms controlling the fracture behavior during cyclic loading are ascribed to the following synergistic influences:

a) Load transfer between the soft Al matrix and the hard Al_2SiO_5 and soft carbon particulate reinforcement.
b) Hardening arising from constrained plastic flow and tri-axiability in the Al matrix due to the presence of Al_2SiO_5/C reinforcements. As a direct result of the particles resisting the

plastic flow of the matrix, especially in chilled composites, an internal stress or back stress is created.

c) Residual stresses generated in the Al matrix arising from the mismatch in thermal expansion coefficients between the soft matrix and the hard reinforcement particulates.

d) During cyclic deformation it seems possible that the mismatch that exists between the reinforcing particles and the ductile matrix favors concentration of stress at and near the particle-matrix interface, causing the matrix in the immediate vicinity to fail permanently or the particle to separate from the matrix. In addition, the improvement in fracture toughness when chills are employed during casting can also be attributed to presence of carbon in the structure of the matrix.

5. CONCLUSIONS

In this paper, characterization of strength and fracture behavior of chilled $Al/Al_2SiO_5/C$ composites cast using different metallic and non metallic chills during solidification was studied. Fractured surfaces were investigated to analyze the fracture mechanisms by SEM. The results can be summarized as follows.

1) Chilled $Al/Al_2SiO_5/C$ composites were successfully fabricated by employing various types of chills. From their microstructure, it was found that, there is uniform distribution of the dispersoid and good bonding between matrix and the dispersoid were achieved.

2) UTS of the chilled composites was increased by increasing the addition of combination of dispersoids up to 12 vol%. High rate heat transfer during solidification is found in case of copper end chill and hence it is found to be more effective than compared with the other type of chills.

3) In the $Al/Al_2SiO_5/C$ composites tested, fracture toughness of the chilled composites were found to increase as the content of Al_2SiO_5/C particulates was increased up to about 12% by volume. Further addition of particulates tends to reduce these two mechanical properties. There is therefore no advantage in increasing indefinitely the Al_2SiO_5/C content combination in such MMCs.If all other factors were kept constant, the faster the heat extraction from the molten MMC during casting, the higher would be the UTS and the fracture toughness of the castings. Fracture behavior of the MMCs cast using copper chills showed mixed mode fracture with isolated micro-cracks on the fracture surface. In contrast, fracture behavior of the MMCs cast without chills revealed ductile failure with separation of Al_2SiO_5/C particles from the matrix.