An overview of thermal expansion behaviour on microstructure formation of Al-base alloy metal matrix composites by centrifugal casting

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Abstract: **Centrifugal casting process is most effective method in recent days to manufacture large quantities of circular components like pipes, tubes, etc. Due to its high temperature and invisible mold, it is difficult to know the mechanism of molten metal inside the mold. Thermal expansion behaviour is strongly influenced by the presence of voids. Voids are formed because of air bubbles being entrapped while pouring molten metal inside the mold and it is correlated to the microstructure, the deformation of the matrix, and the internal stress conditions. Thermal cycling of composites induces thermal stresses which lead to dimensional change. Coefficient of thermal expansion plays a major role in the formation of equiaxed microstructure. Many experimental results showed that the relationship between the CTE of Al/SiCp and temperature is nonlinear. The effects of process parameters like melt temperature, rotational speed, and flow rate were evaluated to develop sound casting.**

Keywords: Coefficient of thermal expansion; microstructure; centrifugal casting

I. Introduction

Traditional heat conducting materials for Power electronic modules and base plates do not meet the demand of having a sufficiently low coefficient of thermal expansion. The constraints of conventional materials have led to tailor the properties by developing metal matrix composites containing high volume fractions of reinforcement particles. The thermal expansion behaviour of such a composite is the result of several material parameters [6]: the constituents and their phase stability, the reinforcement volume fraction and architecture, their arrangement within the composite, the microstructure of the matrix and defects introduced during processing. Due to flexible fabrication techniques, tailorable thermo-physical properties such as high thermal conductivity, compatible coefficient of thermal expansion (CTE).

High volume fraction ceramic particle reinforced with metal matrix composites (MMCs) have been developed for electronic packaging applications, power module base plates, printed wiring board cores, microprocessor lids and insulated gate bipolar transistor. The large difference of CTE between the reinforcement and the matrix could generate an internal stress which could influence the performance of MMCs. The mean linear coefficients of thermal expansion decreases with an increase in volume fraction of reinforcements. The orientation of reinforcement changes the internal stress condition in the composite, which yields anisotropic thermal behaviour. Due to CTE mismatch between the reinforcement and the matrix, residual thermal stress will be induced during cooling from fabrication temperature to room temperature.

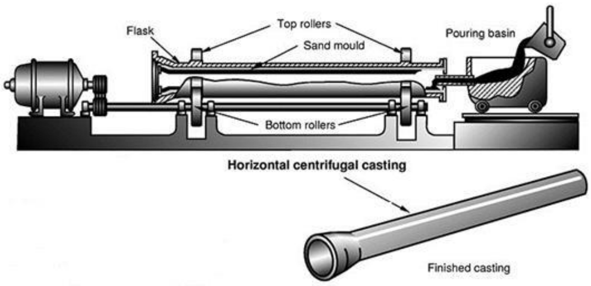
Temperature cycling often exists in the operating environment of electronic components, reinforcement volume fraction of greater than 60% is necessary [3] for coefficient of thermal expansion (CTE) matching with those of electronic components or ceramic substrates to reduce thermally induced stresses and increase the reliability of electronic devices. Also, It is reported that thermal cycling could result in a plastic strain accumulation and sample dimension change. Because of metal-mold rotation, experimental thermal analysis of the centrifugal casting process is more difficult than that of static processes, increasing the importance of the mathematical modeling of heat transfer as an alternative tool.

The significant increase in research activity and publications in temperature analysis of Al base composite materials in the last few years, the present review article is an attempt to recognize and highlight the topics that are most relevant to thermal expansion behaviour of metal matrix composites. Because of the extensive growth in metal matrix composites in the last two decades, it is advisable to reduce the review to a feasible level by concentrating on the thermal expansion behaviour of metal matrix composites only. The review carried out here, is concerned with effects of temperature on development of metal matrix composites, plastic strain, and microstructure. An attempt has been made here, to include all the important contributions in the current area of interest and they are outlined in the conclusions.

II. Centrifugal casting process

Centrifugal casting is a unique form of casting for metal. The casting process occurs inside of a tube-shaped machine that spins rapidly. Centrifugal castings are known for high densities in the outermost regions. Centrifugal casting machines may be either horizontal or vertical-axis. Horizontal axis machines are preferred for long, thin cylinders, vertical machines for rings.

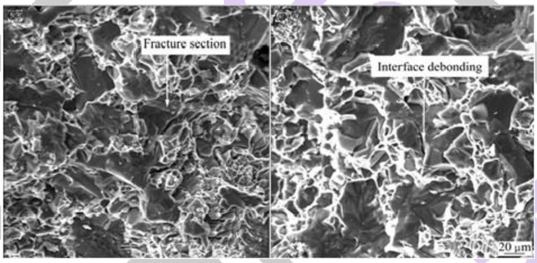
Centrifugal casting uses a permanent mold that is rotated about its axis at a speed between 300 to 3000 rpm as the molten metal is poured. Centrifugal forces cause the metal to be pushed out towards the mold walls, where it solidifies after cooling. Parts cast in this method have a fine grain microstructure, which is resistant to atmospheric corrosion, hence this method has been used to manufacture pipes. Since metal is heavier than impurities, most of the impurities and inclusions are closer to the inner diameter and can be machined away.



Schematic representation of centrifugal casting process

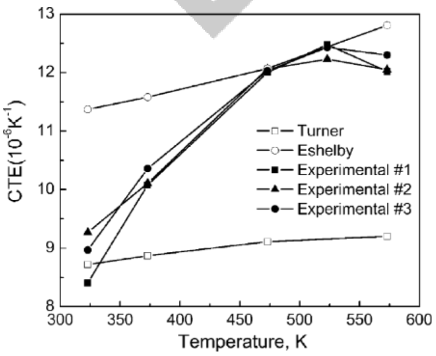
III. Literature Survey

Bo LI et al.[1] have developed aluminum-based in-situ composites reinforced with Mg2Si and Si particles by centrifugal casting Al−20Si−5Mg alloy. The microstructure of the composites was examined, and the effects of temperature on fracture behavior of the composite were investigated. The results show that the average fraction of primary Si and Mg2Si particles in the composites is as high as 38%, and ultimate tensile strengths of the composites first increase then decrease with the increase of test temperature. Microstructures of broken specimens shows that both the particle fracture and the interface debonding affect the fracture behavior of the composites, and the interface debonding becomes the dominant fracture mechanism with increasing test temperature. Comparative results indicate that rich particles in the composites and excellent interface strength play great roles in enhancing tensile property by preventing the movement of dislocations.

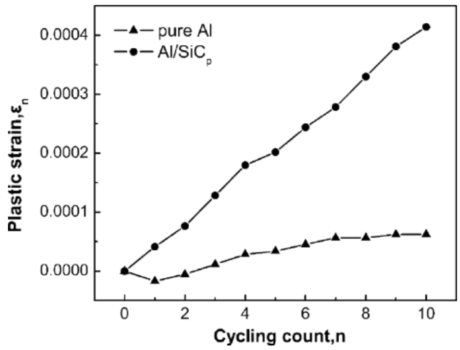


Fracture microstructures of tensile specimens

Na Chen et al.[2] have discussed the effect of thermal cycling on Al/SiCp composite. CTE of Al/SiCp composite versus thermal cycling counts was investigated. CTE of Al/SiCp composite at different temperature has also been studied. The stress in one thermal cycling is composed of an initial elastic segment and a following plastic segment. It could be seen that addition of SiCp can significantly decrease the CTE of aluminum. In their work, Turner and Eshelby models were used to calculate the CTE of Al/SiCp composite. The sharp corner of real SiC particles could induce larger internal stress and the plastic strain of Al/SiCp composite is larger than that of pure Al during thermal cycling. The coefficient of thermal expansion (CTE) and accumulated plastic strain of the pure aluminum matrix composite containing 50% SiC particles (Al/SiCp) during thermal cycling (within temperature range 298–573 K) were investigated. The composite was produced by infiltrating liquid aluminum into a preform made by SiC particles. Experiment results shows that the relationship between the CTE of Al/SiCp and temperature is nonlinear; CTE could reach a maximum value at about 530 K.



CTE at different temperatures for Al/SiCp composite



Plastic strain for pure Al and Al/SiCp composite vs. thermal cycling counts

Qiang Zhang et al.[3] have fabricated Al–Si matrix composite reinforced with 73 vol.% SiC particles by squeeze casting technology. And they have studied microstructure, thermal expansion behavior, coefficients of thermal expansion of SiCp/Al composite and unreinforced matrix. In their work, CTE reaches maximum at 250 and 350^{0}C, and then diminished at elevated temperatures. With the addition of a large content of SiC particles, the CTEs of SiCp/Al composite were reduced greatly to nearly one-third of those of unreinforced matrix. They have Kerner's model was in better agreement with experimental CTEs. In Al–Si alloys, the solute concentration of Si in aluminum increased with increasing temperature, but the lattice parameter of aluminum decreased. The composite was also subjected to a thermal cycling test between 20 and 150^{0}C to evaluate its dimensional stability. A residual length change was observed at the end of cycling test.

Santiago Vacca et al.[4] have determined heat transfer coefficient at the metal-mold interface during the centrifugal casting of a Fe-C alloy tube using the inverse solution method. They have measured the cooling curves within the tube wall under a mold rotation speed of 900 rpm imposing a centrifugal force larger than gravity force. They have developed comprehensive heat transfer model of the centrifugal casting and coupled to an optimization algorithm. It was found that the existence of a centrifugal force enhance the metal-mold contact. The implemented model shows that the heat loss by radiation is dominant over that by convection at the tube inner surface, causing the formation of a solidification front that meets another front coming from the outer surface of the tube.

T. Huber et al.[5] have investigated thermal expansion behaviour of different SiC particulate reinforced aluminium-matrix composites using thermal mechanical analysis equipment. Composites with different SiC contents (10, 20, 55, 70 vol%), various matrix-alloy compositions (Al99.5, A356, A359), and different fabrication routes were investigated. In their work, the expansion behaviour is correlated to the microstructure, deformation of the matrix and the internal stress conditions. The temperature dependence of the solubility of Si in Al influences the CTE of Al–Si matrix alloys significantly. It was found that composites with isolated ceramic particles (10–55 vol%) shows similar thermal expansion behaviour as the matrix alloy just reduced by the volume fraction of SiC-particles.

Tran Huu Nam et al.[6] have studied instantaneous coefficient of thermal expansion of Al-based metal matrix composites containing 70 vol.% SiC particles. In their work, CTE of AlSiC is studied by thermo-elastic models and micromechanical simulation using finite element analysis in order to explain abnormalities observed experimentally. The CTE was modelled for heating and cooling cycles from 20°C to 500°C considering the effects of microscopic voids and phase connectivity. It was found that thermal expansion behaviour is strongly influenced by the presence of voids and confirms qualitatively that above 250 °C CTE decreases.

N.Chawla et al.[7] have studied coefficient of thermal expansion of extruded SiC particle reinforced 2080 Al composites. In their work, CTE were measured using a thermal mechanical analyzer (TMA) and it was found that the anisotropic distribution of SiC particles determines the anisotropic thermal behavior of Al/SiCp composites. CTE in the short transverse direction is higher than that in the longitudinal direction. Finite element modeling (FEM), based on the actual microstructure of Al/SiCp composites, was employed to simulate the thermal behavior. The FEM results showed that orientation of SiC particles changes the internal stress in the composite, which yields anisotropic thermal behavior.

Jan Bohacek et al.[8] have determined heat transfer coefficient (h) at the cast-mold interface from the calculations of air gap thickness based on a plane stress model taking into account thermo-elastic stresses, centrifugal forces, plastic deformations, and a temperature-dependent Young's modulus. In their work, an alternative numerical simulation to the empirical formulas was proposed to describe time-dependent heat transfer coefficient (h). Several numerical tests were performed for different coating thicknesses, rotation rates, and temperatures of solidus. Results revealed that ratio of coating thermal conductivity and its thickness is equal to initial values of h. Then, h drops exponentially when the air gap is formed between cast-mold interfaces.

S Cem OKUMUS et al.[9] have prepared aluminum-silicon based hybrid composites reinforced with silicon carbide and graphite particles by liquid phase particle mixing (melt stirring) and squeeze casting. In their work, thermal expansion and thermal conductivity behaviors of hybrid composites with various graphite contents and different silicon carbide particle sizes (45µm and 53µm) were investigated. Results indicated that increasing the graphite content improved the dimensional stability, and there was no obvious variation between the thermal expansion behaviors of the 45µm and the 53µm silicon carbide reinforced composites. The thermal conductivity of hybrid composites was reduced due to the enrichment of the graphite component.

Rajendra U. Vaidya et al.[10] have measured thermal expansion of various fiber and particle reinforced metal-matrix composites and the experimentally obtained values were compared with the predictions of various theoretical models. It was observed that the particulate composites exhibited some residual strain when cooled down from the peak temperature to room temperature. The magnitude of this strain was a function of the peak temperature and number of thermal cycles. The thermal expansion response of the fiber-reinforced composites exhibited very small residual strains when cooled down from the peak temperature to room temperature. In addition, the thermal expansion response was not linear over the test temperature range but exhibited regions of distinctly different slopes. The observed behavior of these particulate and fibrous composites is described on the basis of the thermal stresses developed in such composites as a result of the differences in the coefficient of thermal expansion between the reinforcement and the matrix.

S.Elomari et al.[11] have developed aluminum-matrix composites containing thermally oxidized SiC particles by vacuum assisted high-pressure infiltration process. In their work, thermal-expansion coefficients (CTEs) were measured between 25 and 500 °C with a high-precision thermal mechanical analyser (TMA), and compared with the predictions of various theoretical models. The thermal-expansion behavior of the three-phase Al/SiC/SiO2 composite shows no significant deviation from the predictions of elastic analysis, since the measured CTEs lie within the elastic bounds derived by Schapery's analysis. It was observed that effect of particle size plays a major role in pressure-infiltrated composites. Thermal expansion was more, when particle has large size and thermal stresses between the reinforcement and matrix was developed due to CTE mismatch.

Masayuki Mizumoto et al.[12] have evaluated bonding strength of the SiC particle/Al-4 %Cu alloy composites fabricated by a low-pressure infiltration process. In their work, thermal cycling test was carried out for 20 vol% and 40 vol% SiC particle/Al-4%Cu alloy composites. It was observed that a reaction layer of less than 1mm thickness was formed at the interface of SiC particle/matrix. This reaction layer was identified as Al_4C_3 formed by the reaction between the alloy melt and SiC particle during infiltration. The coefficient of thermal expansion was hardly changed during thermal cycling for both the 20 vol% and 40 vol% SiC particle/Al-Cu composites. The Vickers microhardness measured on the SiC particles in the specimens having a strongly bound interface show hardness values with a small scatter, while those for the specimens having a weakly bound interface exhibit a large scatter in the hardness values.

IV. Conclusions

An attempt is made to present overview of thermal expansion behaviour on microstructure formation of Al-base Alloy metal matrix composites. From the literatures, it is observed that, the large difference of CTE between the reinforcement and matrix could generate an internal stress which could influence the performance of composites. The CTE were reduced with an increase in volume fraction of reinforcement. The hypereutectic Al-Si alloy was chosen because of its good casting fluidity, lower CTE and better balance of thermal and mechanical properties.

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