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ORIGINAL ARTICLE

Characterization of functionally graded Al-SiC_p metal matrix composites manufactured by centrifugal casting

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Abstract The design of metal matrix composites can be enhanced by integrating the concept of functionally graded materials (FGM) to produce engineering materials with tailored contradictory properties that suit multifunctioning components. The present investigation focuses on characterization of functionally graded metal matrix composites (FGMMCs) based on pure aluminium matrix reinforced with different percentages and sizes of SiC particles. The investigated FGMs have been produced by horizontal centrifugal casting process under different conditions. Microstructure investigation, tensile, hardness and wear rate measurements have been correlated with the size and percentage of SiC particles and their distribution/gradient across the thickness of the cast tubes resulting from the used casting parameters.

1. Introduction

Functionally graded structures can be seen in nature, in bio-tissues of animals, such as bones and teeth, and plants. Dental crowns represent excellent examples of functionally graded structures. They require a high wear resistance outside and a ductile inner structure for reasons of optimal fatigue and brittleness combination [1]. The development of composite materials with graded properties known as functionally graded materials (FGM) has made a revolution in the manufacturing of mechanical parts, especially in the automotive, aviation and biomedical industries [2]. The concept of FGM was first considered in Japan in 1984 during a space vehicle project. That time the aim was to fabricate the body's material with improved thermal resistance and mechanical properties by gradually changing compositions to withstand severe temperature gap (about 1000 °C) in between the inside and the outside [3].

The need for property distributions is found in a variety of common products that must have mutually exclusive requirements to provide multi-functional characteristics. For example, gears must possess high internal toughness to withstand dynamic loading and superior surface hardness to prevent wear [4]. Similarly, a turbine blade also possesses a property distribution. The blade core must be tough enough to withstand the heavy dynamic loading it is subjected to, while its

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surface must have a high melting point to be able to withstand high temperatures encountered during operations. As with hardness and toughness, these different properties tend to exclude one another. There are many applications for FGMs in aerospace, power generation, electronics and bioengineering which demand properties that are not achievable in any single material [5].

FGM materials are manufactured using different techniques including powder metallurgy [6,7], vapour deposition [8], solid freeform (SFF) fabrication [9], centrifugal slurry or centrifugal casting [10]. The production of FGM using centrifugal casting involves the addition of hard particles to a molten metal and pouring the mixture into a rotating cylindrical mould. The composite is solidified on the internal wall of the mould under centrifugal force, with gradient of the hard particles depending on the size of particles, mould rotational speed, density and viscosity of the molten metal as well as the rate of solidification [11].

FGMs are manufactured to achieve pre-required gradient in strength, corrosion, wear or high temperature resistance across the wall thickness of the product. Weight saving can be achieved in functionally graded castings compared to casting made entirely from MMCs [12].

Various researchers have carried out the researches on FGM with focus on mathematical modelling and simulation of the particles [13,14] and the production processes [15–17] while others focused on characterization of the mechanical, tribological as well as microstructural characterization of FGMs prepared using different production techniques [18].

Rodriguez-Castro studied the effect of adding 23 μm SiC_p on the resulted microstructure and mechanical behaviour of centrifugally cast aluminium alloy A359/SiC_p [19]. He investigated the microstructure, hardness, tensile strength and fatigue fracture behaviour of FGMs by varying the percentage of SiC_p between 20% and 40% and rotational speed between 700 rpm and 1300 rpm. A maximum increase of nearly 15% in tensile strength and surface hardness could be achieved by the addition of 20% SiC_p at 1300 rpm compared to the base A359 alloy.

Rajan and Pillai (2008) fabricated discs from A356 alloy by adding 20 wt.% of 23 μm SiC_p to the FGMs produced by vertical centrifugal casting. They studied the effects of reinforcement on microstructure, hardness, ultimate tensile strength, and yield strength. Ultimate compressive strength and modulus of elasticity of the samples taken from the FGM disc had been determined [20]. A maximum increase of nearly 26% in hardness and 18% in tensile strength of outer layers could be achieved compared to the base A356 alloy. In 2010 they extended their work and compared the characteristics of FGM based on cast A356 and wrought AW2124 aluminium alloys reinforced with 15 wt.% of 23 μm SiC_p [21]. For the A356/15 wt.%SiC_p composite, a maximum increase of nearly 38% in outer layers hardness could be achieved compared to the base alloy. On the other hand, only 28% increase in outer layer hardness could be reached in case of composites made of AW2124/15 wt.%SiC_p.

Vieira and Sequeira (2009) studied the effects of reinforcement of SiC_p on sliding wear behaviour of centrifugally cast Al–10Si–4.5Cu–2 Mg alloy reinforced by 10 wt.% of 37 μm SiC_p. The centrifugal casting processes were performed at 2000 rpm. By varying wear load and track velocity, they concluded that SiC_p reinforced material has better wear resistance with increase of SiC_p content [22]. Brinell hardness of 160 BHN could be reached at outer layers, while the hardness of the inner layers recorded 105 BHN. Wear loss in the order of 0.01 mg was recorded at outer layers, compared to 10 mg weight loss in the base non-reinforced alloy. Although this investigation resulted in very high hardness and wear resistance levels, it did not show the negative influences on tensile and ductility properties.

Vikas and Maiya (2014) fabricated functionally graded rings using vertical centrifugal casting process. The composite rings were made of AA6061 reinforced with 10 wt.% SiC_p of 23 μm particle size. They investigated the microstructure and evaluated the hardness and wear rate behaviour of the FGM rings under different loading levels. The measured hardness levels at outer layers reached a maximum of 80 BHN. This represents 38% higher than the hardness measured at the inner layers of the cast rings [23].

Jayakumar and Rajan (2016) characterized functionally graded metal matrix composites (FGMMC) made of A319 alloy reinforced with 23 μm SiC_p. Rings of FGMs with 10 and 15 wt.% SiC_p were produced by vertical centrifugal casting process. The researchers evaluated the mechanical characteristics in addition to the microstructure, coefficient of thermal expansion and wear behaviour of FGMs [24]. The authors referred to the presence of an outer chill zone, but the maximum hardness was measured at the adjacent inner zones towards the centre. Maximum Brinell hardness (65 BHN) has been measured in composites with 10 wt.%SiC_p at the outer zones, compared to 45 BHN at the inner zones, whereas the maximum strength has been measured in case of samples taken from the outer zone only for composites containing 15 wt.%SiC_p.

Recently, Radhika and Raghu (2016) investigated the behaviour of FGMs produced from A319 alloy reinforced with B_4C, SiC, Al_2O_3 or TiB_2. They compared the microstructure, hardness, tensile strength and wear rate [25]. The maximum tensile strength could be achieved by adding 10 wt.%TiB of 10 μm particle size, while the maximum outer zone hardness is realized by adding 15 wt.%SiC of 23 μm particles.

The given review shows that there is a focus on using Al-Si alloys (e.g. A356), which possess higher strength and hardness, but lower melting temperature and viscosity compared to pure aluminium. This may facilitate the production of the FGM by expanding the window available for pouring and results in higher strength composites. In addition, the existence of Si within the melt prevents the dissolution of SiC_p [26] and the formation of the hydrophilic and brittle Al_4C_3 [27]. The formation of this carbide at the matrix/SiC_p interface reduces the interfacial strength as well as the fracture energy and increases the corrosion sensitivity [28].

However, the lower melting temperature of Al-Si alloys makes the FGM more vulnerable to softening in high temperature applications. In addition, the cost of the alloy is higher than that of pure aluminium, which introduces involvement of economic consideration to the FGM cost.

In this study, the investigations were carried out using commercially pure aluminium to find out a suitable procedure to produce centrifugally cast FGM products in the tight available pouring time. The effect of higher pouring temperature and hence the lower molten metal viscosity on the distribution of the SiC particles was investigated. Moreover, the large temperature gradient between the molten metal and the mould should

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