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Brief Introduction

This book entitled " Fabrication, microstructure and mechanical properties of submicron/micron $SiC_p/AZ91$ magnesium matrix composite" summarizes the authors'10 years of research results on the field of particle reinforced magnesium matrix composite (PMMC). By reviewing the stirring casting process, recrystallization behavior, interface and fracture mechanism of PMMC, this book proposes that the PMMC with high strength is meaningful to meet the requirements of light material with high specific strength, and high specific modulus in the area space and aviation. Firstly, one kind of PMMC (10μm 10vol. % $SiC_p/AZ91$) was selected to investigate the forging effects on the microstructure, particle distribution, texture and mechanical properties of the composites. After that, the particle size's influence on the microstructure, recrystallization, mechanical properties, room temperature deformation mechanism, strengthening effect and fracture mechanism is given and analyzed. Based on above research, a new kind PMMC ((micron + submicron) $SiC_p/AZ91$ composite) is designed and fabricated. Influence of bimodal size SiC_p on the microstructure, mechanical properties, strengthening mechanism and fracture behavior of this kind composites are revealed and discussed. This book will be helpful for the development, microstructures and mechanical properties control of high strength magnesium matrix composite.

Preface

Magnesium matrix composite overcome the defects of Mg possess high specific strength, specific modulus, wear resistance and lower coefficient of thermal expansion, which can further broaden magnesium's application in the future. According to the type of reinforcement, the composite can be divided into continuous fiber, short fiber, whisker and particle magnesium matrix composites. Among these composites, the particle reinforced magnesium matrix composite fabricated by stir casting, possess the merit of lower production cost and simple technological process, et al, which is the most promising composite to realize mass production.

Even though the casting methods are simple and economical, the application of as-cast magnesium matrix composites is restricted due to their low mechanical properties caused by micro-voids formed in the matrix during stir casting. To improve the mechanical properties of the as-cast composites, second processing, such as rolling, extrusion or forging have been applied. By the using of forging and extrusion, porosity can be minimized or eliminated, meanwhile, both the particle distribution and interfacial bonding are improved. All these contribute to the increased strength and ductility of composite. Recently, two-step deformation process has been applied successfully in magnesium alloys, which demonstrates significant grain refinement. In this book, the SiC_p/AZ91 composite will be applied by two-step (forging+extrusion) deformation process, the microstructure and mechanical properties will be given and discussed.

Generally, particle size also has obvious effect on the mechanical properties of composite. Micron particles distribute uniform in matrix and can improve the matrix's yield strength and modulus significantly. The particles will demonstrate better strengthening effect with decreasing particle size. However, the particle agglomeration appears as the increasing volume fraction of fine particles (especially as the particle size less than 1μm), which limits the enhancement of modulus. To give a full play of the merits of different particle size, the mixture of (submicron + micron) particles are meaningful. In this book, the influence of micron and submicron SiC_p on the microstructure and mechanical properties of the composite will be discussed in detail. Then the obtained results are helpful to the design of (submicron + micron) bimodal size SiC_p/AZ91 composite.

Through the research of (submicron + micron) bimodal size SiC_p/AZ91 composite, the results show that the strengthening effect of bimodal size SiC_p is better than single size SiC_p, and the highest mechanical properties of composite could be obtained at the volume ratio of 1 : 9 between submicron and micron SiC_p. The interface bonding between micron/submicron SiC_p and AZ91 matrix is better, and definite orientation relationship were found between submicron SiC_p and AZ91. Dislocation piled up in the vicinity of submicron and micron SiC_p due to hinder effect of particles during room deformation, which led to the increased dislocation density around SiC_p. Under external load, micocracks initiate predominately at the ends of micron SiC_p and particle rich regions due to stress concentration. While, interface bonding between submicron SiC_p and matrix is better, and no microcracks can be found. Dispersed submicron SiC particles around micron SiC_p can hinder crack propagation. Microcracks propagate along the interface between micron SiC_p and matrix as increasing load. Once microcracks throughout the matrix, they will link together quickly, leading to the fracture of composites.

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Contents

Chapter 1

Introduction

As the lightest metal structural metallic materials in natural, Mg and its alloys process the high specific strength, specific modulus, damping capacities and better processability, which have been applied in the area of automobile, aviation, electron and space, etc[1,2]. However, the lower modulus, strength and wear resistance limits their application in industry as structural materials. As compared with Mg alloys, the magnesium matrix composite has high specific strength, specific modulus, wear resistance and lower coefficient of thermal expansion, which can further broaden magnesium's application in the future[3-5].

Fabrication of composite originates from continuous fiber reinforced composite[6]. But the complex fabrication and high production cost limit its application. For a comparison, particle reinforced composite can offset the inadequacy of continuous fiber reinforced composites and has been applied in some area[7]. Among all kinds of fabrication process of composite, stir casting technology possess the merit of lower production cost and simple technological process, et al, which is most potential to realize mass production of the composites[8,9].

Even though the casting methods are simple and economical, the application of as-cast magnesium matrix composites is restricted due to their low mechanical properties caused by micro-voids formed in the matrix during stir casting. So it is necessary to improve the mechanical properties of the as-cast composites by second processing, such as rolling, extrusion or forging. Some studies demonstrate that forging and extrusion can minimize or eliminate porosity, lead to a more uniform particle distribution and also improve the particle-matrix interfacial bonding, with a subsequent increase in strength and ductility[7,9-14]. Two-step processing route has a significant effect on reducing grain size and improving the mechanical properties of magnesium. El-Morsy[15] obtains the finer grain size and improved tensile properties of AZ61 magnesium alloy processed by a combination of hot extrusion and thermomechanical processing. Matsubara[16] applies the extrusion and equal-channel angular pressing (ECAP) to a cast Mg-9% Al alloy, and the grain size is reduced from 50μm in the cast alloy to 12μm after extrusion and 0. 7μm after extrusion and ECAP. For particle reinforced magnesium matrix composites, however, most of papers focus on the effect of forging or extrusion on the composites, respectively. While relatively few, not conclusive, results are reported in the literature on the effect of using a two-step processing route in which the composite is initially forged and then subjected to extrusion.

The size of reinforcement has obvious effect on the microstructure of composite. Based on Humphreys et al's[18,19] research of the static recrystallization behavior of Al matrix composite, the particle can promote recrystallization nucleation and growth as its size larger than 1μm, however, the particle can pin grain boundary and impede recryatallizaion as its size finer than 1μm. For the ($<1\mu m$ + $>1\mu m$) bimodal size particle reinforced composite, the large ($>1\mu m$) particle provide nucleation site and the recrystallization kinetic is controlled by fine ($<1\mu m$) particles[19,20]. However, Mg with close-packed hexagonal (HCP) crystal structure has very limited number of slip systems in contrast to aluminum with face-centered cubic (FCC) crystal structure, so stress concentration is easily generated which leads to the increase of the dislocation density. Meanwhile, the stacking fault energy of magnesium (60-78mJ/m^2) is much lower than that of aluminum (~200mJ/m^2), which is beneficial to DRX nucleation. Besides, compared with aluminum, the high grain boundary diffusion rate of magnesium is much easier to absorb dislocation. Thus, influenced of particle size on Mg may different from Al. Up to now, few works haven been done on the recrystallization behavior of magnesium matrix composite influenced by particle size.

The size of reinforcement also has obvious effect on the mechanical properties of composite. It has been shown that micron particles distribute uniform in matrix and can improve the matrix's yield strength and modulus significantly[20]. With the increase of particle size, the particle's surface defect increase and the interface bonding between particle-matrix weakens, which is adverse to the improvement of mechanical properties. As the particle size is finer than 1 μm, the particle's surface defect decreases, which possess better strengthening effect. As compared with micron SiC_p, the fine (< 1 μm) particles can pin dislocation and result in Orowan strengthening and obvious dislocation strengthening[21,22]. So, a little amount of fine particle significant improve the matrix's yield strength and ultimate tensile strength. However, the particle agglomeration appears as the increasing volume fraction, which limits the enhancement of modulus. So the mixture of a little amount submicron particles and micron particles might have significant influence on microstructure and mechanical properties. However, few works had been done on bimodal size particle reinforced magnesium matrix composite at present.

As a consequence, the micron, submicron and (micron + submicron) SiC_p/AZ91 composites are designed and fabricated in this book. Then the particle size effect on the microstructure, recrystallization, mechanical properties, room temperature deformation mechanism, strengthening and fracture mechanism will be given.

1.1 Research of Discontinuous Reinforced Magnesium Matrix Composite

Fabrication of composite originates from continuous fiber reinforced composite[6]. For the better mechanical properties of graphite fibre reinforced magnesium matrix composite, it had been applied in the aerospace field[23]. Even though some investigations are still doing on continuous fiber reinforced composite, their application is limit for the complex fabrication and high production cost. For a comparison, particle and whisker with high strength and low price can offset the inadequacy of continuous fiber, which is becoming more and more attention now. The particles include SiC_p[24], TiB_{2p}[25], TiC_p[26] and B_4C_p[27]. The whiskers mainly include SiC_w[28] and $Al_{18}B_4O_{33w}$[29]. To improve the casting ability of the composite, the AZ91, AZ31 and ZK60 are usually selected as matrix which contains Al and Zn element[2].

The microstructure and mechanical properties of SiC_w reinforced Mg matrix composite has been investigated widely at present[30]. On Hu et al's[31] investigation of SiC_w reinforced Mg matrix composite, the modulus and ultimate tensile strength (UTS) are increased obviously as compared with matrix alloy. Besides, the particle reinforced magnesium matrix composites are investing widely at present for the lower price of particles[2]. The SiC_p reinforced magnesium matrix composite has been applied in automobile and aerospace, etc. in abroad[32]. The research has been done on $(SiC_w + B_4C_p)$/ZK60 magnesium matrix composite by Zhang in Shanghai Jiao Tong University in China[33]. The technology and property of B_4C_p reinforced magnesium matrix composite had been investigated by Hao in National University of Defense Technology[34]. About 20 years has been done on magnesium matrix composite in Harbin Institute of Technology[1], which can fabricate large (diameter 350mm, height 500mm) 20 vol. % SiC_p reinforced magnesium matrix composite. Besides, two kinds of pipe with the inner diameter of 130mm[35] and 200mm[36], respectively, are obtained. Such great progress in particle magnesium matrix composite will promote the application of Mg.

Up to now, the research mainly focuses on micron particle reinforced magnesium matrix composite. About the influence of particle size and volume fraction of micron particle on the microstructure and mechanical properties still need further investigation. Especially, as the particle is less than 1 μm, which influnce on microstructure and mechanical properties of the composite may different from micron particle. Unfortunately, the effect of fine particle ($<1\mu m$) and bimodal size particle reinforced magnesium matrix composite are still unclear.

1.2 Stirring Casting Process of Discontinuous Reinforced Magnesium Matrix Composites

The main fabrication process of discontinuous reinforced magnesium matrix composites include melt infiltration[37], spray deposition[38], powder metallurgic[39,40], in situ reaction antigenic reinforcement[41] and stir casting[9], etc. Among all kinds of fabrication process of composite, stir casting technology process merit of lower production cost and simple technological process, etc, which is most potential to realize mass production of the composites. According to the alloy state during stirring, the stirring casting method can be divided into fully liquid and semi-solid stir casting. The composite fabricated by fully liquid usually exhibit poor mechanical properties for the existence of pores and agglomerated reinforcement[42]. However, the semi-solid stir casting overcome above defect of fully liquid, which has been investigated widely in recent years[43-45].

The micron SiC_p reinforced magnesium matrix composites were fabricated by Poddar et al[46], it showed that addition of micron SiC_p is propitious to grain refinement and this phenomenon become much more obvious with decreasing particle size. The SiC_p/AZ91 composites had been fabricated successfully by Wang[9], the obtained YS, UTS and modulus of as-cast and as-extruded SiC_p/AZ91 composites are shown in Table 1 - 1 and Table 1 - 2, respectively. Wang's results indicate that the existence of micron SiC_p has obvious effect on improving YS, UTS and modulus of AZ91 matrix. After the application of hot extrusion, the YS, UTS and elongation can be further improved. Moreover, Dong's[35,36] work had proved that the large SiC_p reinforced magnesium matrix composite can be obtained by semi-solid stir casting. Besides, the pipe with the inner diameter of 200mm can be obtained after hot extrusion[35,36]. Thus, it is meaningful to investigate the hot deformation behavior of particle reinforced magnesium matrix composite fabricated by stir casting.

Table 1 – 1 Mechanical properties of as-cast SiC_p/AZ91 composites fabricated by stir casting[9]

Materials	YS/MPa	UTS/MPa	Modulus/GPa	Elongation/%
AZ91	75	191	43	7.2
10μm5% SiC_p/AZ91	111	214	52	2.3
10μm10% SiC_p/AZ91	126	191	55	0.5
10μm15% SiC_p/AZ91	148	166	67	0.35

Table 1 – 2 Mechanical properties of as-extruded SiC_p/AZ91 composites[9]

Materials	YS/MPa	UTS/MPa	Modulus/GPa	Elongation/%
AZ91	169	293	43	29.6
10μm5% SiC_p/AZ91	193	279	48	7.3
10μm10% SiC_p/AZ91	249	327	60	4.3
10μm15% SiC_p/AZ91	276	374	67	2.3

1.3 Recrystallizaion Behavior of Particle Reinforced Magnesium Matrix Composites

As compared with Al, the stacking fault energy of Mg is much lower, which result in the difficult start of cross slip. Moreover, Mg with Hcp crys-