Theoretical Analysis of Particle Segregation in Centrifugally Cast Functionally Graded Magnesium Composites

SALEH Bassiouny[1,2*], *FATHI Reham*[3], *ABDALLA Modawy Adam Ali*[4], *SHANKAR Karthik V*[5], *RADHIKA N*[6]

1. College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R. China; 2. Production Engineering Department, Alexandria University, Alexandria 21544, Egypt; 3. College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R. China; 4. College of Energy and Electrical Engineering, Hohai University, Nanjing 211100, P.R. China; 5. Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amritapuri 690525, India; 6. Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Coimbatore 641112, India

(Received 5 May 2023; revised 10 July 2023; accepted 28 July 2023)

Abstract: The paper investigates the effect of main parameters on particle distribution in centrifugally cast magnesium matrix composites using theoretical and experimental studies. The study aims to depict solidification impacts on particle movement, along with other main forces. The findings demonstrate that the rotation speed, solidification interval, and density differential between the matrix and particles affect the thickness of the particle-segregated zone caused centrifugal force. Additionally, the comparison of SiCp distribution in the AZ91 matrix composite between the theoretical model and experiments shows that the proposed analysis is acceptable at 10% (in weight) at the middle zone. The difference between the experimental and theoretical results is 5.83%, 10.20%, and 4.86% in the outer region and 2.64%, 1.58%, and 2.36% in the middle region for each of 5%, 10%, and 15% (in weight) composites, respectively.

Key words: functionally graded materials; theoretical analysis; centrifugal force; AZ91 alloy; particle segregation

CLC number: TB33 **Document code:** A **Article ID:** 1005-1120(2023)S2-0110-11

0 Introduction

The progress of materials daily improves material qualities, constrained usage of accessible materials, such as pure metals, alloys, and traditional composites, which cannot be regulated to attain the requisite attributes acceptable for many purposes. In the past, engineering materials were created to make goods with homogeneous features, which exhibit little or no variation in the characteristic when finished and could give maximum efficiency for commercial applications in various industries. Nonetheless, due to the limitations of using traditional homogeneous materials, such as pure metals, alloys, ceramics, polymers, and traditional composites, it was necessary to develop new materials with opposing properties and a graded structure to fulfil the needs of industrial development applications[1-2]. Most sectors, including aerospace, transportation, power, and communications, have concentrated heavily on the use of lightweight parts in recent years for a variety of reasons, the most significant of which is to lower project costs and maintains compliance with rules and standards[3]. Magnesium (Mg) alloys have been the most popular material for meeting the rising need for lightweight metal alloys due to technical advantages such as excellent strength-to-density ratio[4-6]. However, additional constraints, including poor corrosion resistance, low room tem-

*Corresponding author, E-mail address: bassiouny.saleh@alexu.edu.cn.

How to cite this article: SALEH Bassiouny, FATHI Reham, ABDALLA Modawy Adam Ali, et al. Theoretical analysis of particle segregation in centrifugally cast functionally graded magnesium composites[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2023, 40(S2): 110-120.

http://dx.doi.org/10.16356/j.1005-1120.2023.S2.015

perature formability, and low wear resistance, limit their usage in many applications[7-8]. By incorporating solid particles into magnesium matrix alloys, magnesium matrix composites have been utilized to overcome this issue[9-10]. However, with the increase of solid phase concentration in magnesium matrix composites, the weight of the magnesium matrix increases, and the particle aggregation increases, thus weakening the magnesium matrix[11-12].

Recently, the researchers employed the advanced category of heterogeneous composite materials, known as functionally graded materials (FGMs), to obtain desired matrix characteristics in a given region, resulting in weight reduction and a lack of an aggregation of particles inside the matrix. FGMs are classic composite materials, but the phase distribution is not regulated to generate a smooth gradient to manage and achieve the required qualities[13]. FGM has grown desirable because of its multifunctional qualities, including the reinforced ceramic properties, matrix metal properties, and their combined properties. The key benefits of the FGM are the gradual change of characteristics, such as coefficient of heat conductivity and electrical conductivity, thermal stress, etc, resulting from the gradient distribution of its structure and reinforced phases, which can avoid the damage wrought by the attributes mismatch at high temperature[14-15]. The forecasting of progressive dispersion of particles and the design of structure of FGM are important to get particular qualities to suit the demand of special usage[16-17]. Various researchers have conducted FGM research in recent years, with a focus on mathematical modeling and simulation of the particles and production processes, while others focused on mechanical, tribological, and microstructural characterization of FGMs prepared using various production techniques[18-19]. To show an example, Raju and Mehrotra[20] proposed a mathematical model to find the particle motion in the centrifugal casting of the metal-ceramic composite. The proposed model was simulated, and the results showed that rotation speed positively affected gradient formation. The model equations were solved to evaluate the thickness of the particle-rich region, the solidification time, and the temperature distribution within the casting and mold regions for various operating conditions. The variables examined included the rotational speed of the mold, the heat transfer coefficient between the cast-mold interface, the initial temperatures of the liquid metal and the mold, and the thermophysical properties of particles. The effects of viscosity and rotating speed on centrifugal force, particle segregation, particle dispersion, and mechanical characteristics were modelled by Poolthong et al[21]. The major particle dispersion along the radial direction is produced by the centrifugal action. Particles are more concentrated on the outer than on the inside. Because of the high viscosity area, a "wall" appears in the center of samples for a large proportion of solid samples, making the particle movement difficult. Babu et al.[22] stated that when centrifugal force was applied to castings, the particle distribution in the metal matrix during solidification could be controlled, thus becoming an important and fruitful technology for the production of cast parts with graded structures and properties. They simulated the motion of SiC particle gradation in a 2124-aluminum matrix using the centrifugal casting setup. The centrifugal force is primarily determined by the density difference between the phases, the rotation speed of the mould, particle size and shape, melt viscosity, particle volume fraction, cast ring thickness, and solidification time. Ogawa et al.[16] studied the mobility of each particle in molten metal by simulating the graded distributions of two types of solid spherical particles under centrifugal force. The particles had a large diameter with a low density and a tiny diameter with a high density. They examined the best fabrication conditions for a metallic FGM ring with a unique density gradient, taking into account the influence of dispersed particle diameter and density variations on migration rate and the feasibility of multifunctional FGM. Naher et al.[23] established a mathematical model for determining particle dispersion in metal ceramic composite centrifugal casting. The suggested model was simulated, and the findings revealed that the particle size has a significant influence on gradient development. The factors investigated include the mold's rotating speed, viscosity, particle size, and cooling rate. Balout and Litwin[24] proposed a mathematical formulation based on one-dimensional heat transfer analysis that took into account the change of thermo-physical characteristics caused by particle mobility in the matrix. They discovered that particle segregation was affected by the mold's rotational speed, the size of the reinforcing material, the relative density difference between the matrix and the reinforcement material, the initial pouring temperature of the liquid melt, the mold's preheating temperature, the heat transfer coefficient at the casting/mould interface, and the initial volume fraction of particulates in the melt. The heat-transfer coefficient at the casting/mould interface, as well as the initial temperatures of the liquid melt and the mould, have the greatest impact on solidification time. While Ref.[25] proposed a mathematical model to determine particle motion in the centrifugal casting of metal ceramic composite, which is primarily determined by forces acting on particles, mould rotational speed, melt viscosity, particle weight fraction, thickness, and solidification rate. In terms of functionally graded magnesium matrix composites, Fathi et al.[26] used the horizontal centrifugal casting method to make FGMs from AZ91D Mg alloy reinforced with SiC particles, and studied the effect of particle weight fraction on microstructure behaviour and mechanical properties. According to their findings, adding hard particles to the soft AZ91 matrix greatly improved the mechanical properties of graded composites compared with unreinforced alloys. Saleh et al.[11] employed the centrifugal casting to make graded composites from Mg alloy supplemented with SiC particles, and examined the effect of mould rotational speed on wear resistance for automotive components. Their results showed that raising the mould speed induced the evacuation of particles with a larger density on the outer surface, which improved wear resistance compared with the soft matrix. According to Ref.[11], there is no information available on the influence of primary parameters on magnesium matrix composites with gradient behavior using theoretical analysis. As a result, the goal of this paper is to gather information related to experimental and theoretical work to understand how the factors involved in the process affect the particle distribution within the thickness and hence the characteristics of the samples obtained.

1 Theoretical Formulation

1.1 Theoretical analysis of particle concentration

In the centrifugal action, solid particles in the melt will move due to the density differential between the particle and the molten metal to generate the gradient. The mold of the centrifugal casting is of cylindrical shape[27]. In order to simplify the analysis, suppose that the solidification rate R of melt is constant and that there is no contact between particles and the liquid metal. The weight fraction of particles that migrate into the solidified layer $S_{A'BCD'}$ (Fig.1) in time of Δt is X_L. S_{ABCD} the unit length composite is considered. The AD in Fig.1 is a boundary within which the particles will flow via the $A'D'$ solid/liquid interface for a duration of Δt, therefore, the particle volume fraction in solidified layer X_S is

$$X_\mathrm{S}=\frac{X_\mathrm{L}\,S_{ABCD}}{S_{A'BCD'}}=\frac{(2r-AB)}{(2r-A'B)A'B}X_\mathrm{L} \tag{1}$$

where X_L is the particle weight fraction in melt; S the area; r the radial coordinate; $AB=(R+v_r)(\Delta t\rightarrow 0)$, v_r the radial velocity of particles in melt, and R the solidification rate. When $\Delta t\rightarrow 0$, $AB\ll 2r, A'B\ll 2r$, so X_S can be written as

$$X_\mathrm{S}=\left(1+\frac{v_r}{R}\right)X_\mathrm{L} \tag{2}$$

$$k=\frac{X_\mathrm{S}}{X_\mathrm{L}}=1+\frac{v_r}{R} \tag{3}$$

where k is the distribution coefficient of particles between the solidified layer and melt.

The term X_L in Eq.(1) is varied with the movement of particles in the centrifugal field; it is derived by the continuous theory that

$$\frac{\Delta X_\mathrm{L}}{\Delta t}=\frac{2\pi r\left[X_\mathrm{L}(r)v_r(r)-X_\mathrm{L}(r+\Delta r)v_r(r+\Delta r)\right]}{2\pi r\Delta r} \tag{4}$$

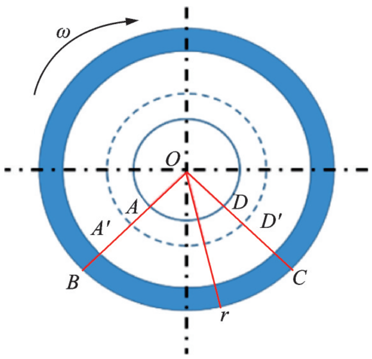


Fig.1 Graphic diagram for calculating particle distribution in a centrifugal zone (In the time of Δt, particles in the $ABCD$ region will be absorbed by the solidified layer $A'BCD'$ and $A'D'$ represents the solid/liquid interface)

as $\Delta t \to 0$, $\Delta r \to 0$, it becomes

$$\frac{\partial X_L}{\partial t} = -\left(X_L \frac{\partial v_r}{\partial r} + v_r \frac{\partial X_L}{\partial r}\right) \tag{5}$$

When particles are assumed to be spherical in shape and the fluid is laminar flow, that is, the Reynolds number $Re \leqslant 1$, v_r can be calculated using Stokes law to be[28]

$$v_r = \frac{d_p^2(\rho_p - \rho_m)\omega^2 r}{18\eta} = A\omega^2 r \tag{6}$$

where A is the material parameters given by $A = \frac{d_p^2(\rho_p - \rho_m)}{18\eta}$, d_p the diameter of the particle, ρ_p the density of the particle, ρ_m the density of the matrix alloy, η the viscosity of melt, and ω the angular velocity. After integration, if assuming ω is a constant, we have

$$\frac{\partial X_L}{\partial t} = -A\omega^2\left(X_L + r\frac{\partial X_L}{\partial r}\right) \tag{7}$$

The initial and boundary conditions are as follows: as $t=0$, $X_L(r,0)=X_L$, $r \leqslant r_o e^{A\omega^2 t}(\Delta\rho > 0)$ or $r \geqslant r_m e^{A\omega^2 t}(\Delta\rho < 0)$, $X_L(r, t)=0$. In Eq.(7), the item $\frac{\partial X_L}{\partial t}$ can be neglected by the comparison of the numerical solution of Eq.(5) with its analytical solution assuming $\frac{\partial v_r}{\partial r}=0$; so, it can be expressed as

$$\frac{\partial X_L}{\partial t} = -A\omega^2 \mathrm{d}t \tag{8}$$

by integrating

$$\int_{X_{L^*}}^{X_L} \frac{\partial X_L}{\partial t} = -\int_0^t A\omega^2 \mathrm{d}t \tag{9}$$

where X_{L^*} is the particle volume fraction in the melt added in the mold before the centrifugal casting. Using this equation, Eq.(1) can be expressed as

$$X_S = X_{L^*}\left(1+\frac{v_r}{R}\right)e^{-A\omega^2 t} \quad r_f \leqslant r \leqslant r_o \tag{10}$$

where r_f is the radius of the particle filling zone (Fig.2), r_o the outer radius of the composite (Fig.2), and t the solidification time given by $t = \frac{r_o - r}{R}$.

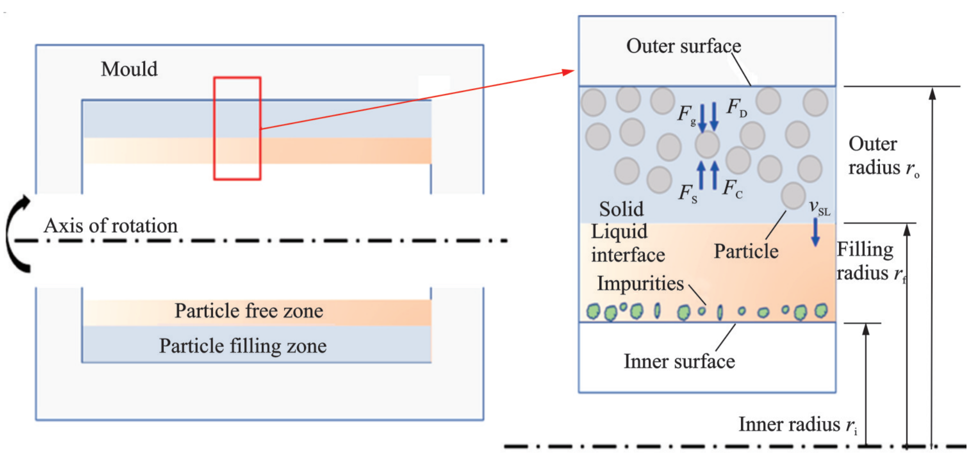


Fig.2 Schematic representation of forces in the molten metal acting on a moving hard particle

1.2 Theoretical analysis of force balance on particles

During the centrifugal casting, a solid particle suspended in the molten metal is subjected to various forces, such as centrifugal force (F_C), viscous force (F_D), repulsive force (F_S), and gravitational force (F_g), as shown in Fig.2. As a result, the force balance (F_{net}) equation can be written as[29]

$$F_{\text{net}}=F_{\text{C}}+F_{\text{S}}-F_{\text{D}}-F_{\text{g}} \tag{11}$$

The gravitational force can be ignored in the previous equation because the centrifugal acceleration is significantly greater than the gravitational acceleration. Furthermore, the effect of the repulsive force on the particle is only considered when the particle is near the solid-liquid interface. The dynamic equation for particle movement can be written as a second-order differential equation based on Newton's second law, as shown below

$$\frac{4}{3}\pi R_p^3\rho_p\frac{\mathrm{d}^2 t}{\mathrm{d}t^2}=\frac{4}{3}\pi R_p^3(\rho_p-\rho_m)\omega^2 r(t)-6\pi R_{\text{p}}\eta_{\text{o}}\frac{\mathrm{d}r}{\mathrm{d}t} \tag{12}$$

where R_p is the radius of the particle (μm), ρ_p the density of the particle, ρ_m the density of the matrix alloy (kg/m^3), η_{o} the viscosity of melt (Pa·s), and r the radial coordinate (centrifugation radius). Under zero acceleration, the final solution of Eq.(12) for particles that move at a constant speed gives their position at any time t

$$r(t)=r_0\exp\left[\frac{4R_p^2(\rho_p-\rho_m)\omega^2 t}{18\eta_{\text{o}}}\right] \tag{13}$$

where r_0 is the position of the particle at time $t=0$. When the liquid metal is overheated, the extraction of the superheat could last for a short or long time before the onset of solidification, depending on the initial pouring temperature, the molding conditions, and the cooling rate. It is well known that the viscosity of the melt increases as the number of particles in the molten metal increases. Eq.(14) describes the viscosity of a melt containing solid particles with a weight fraction less than 20%[30]

$$\eta=\eta_{\text{o}}(1+2.5X_{\text{L}}+10.05X_{\text{L}}^2) \tag{14}$$

2 Results and Discussion

2.1 Evaluation of particle concentration

In this section, the experimental results of functionally graded magnesium matrix composites studied by Ma et al.[11,26] are used to test the proposed theoretical prediction of the concentration of hard particles within AZ91 matrix alloys from the outer surface to the inner surface of the graded composites, and the experimental results are compared with theoretical values. Furthermore, this comparison contributes to gaining a better understanding of the gradient and distribution behaviors of particles inside the matrix as production parameters such as mold speed and weight fraction change. Table 1 contains all of the thermophysical material data and operating parameters used in the theoretical analysis in this paper.

Table 1 Thermophysical material data and operating parameters

Parameter	Value
Outer radius of FG composite r_{o}/mm	90
Inner radius of FG composite r_{i}/mm	70
Radius of the particle R_p/μm	10
Weight fraction of the particle w_f/%	5, 10, 15
Density of the particle ρ_p/(kg·m^{-3})	3 200
Density of the matrix alloy ρ_m/(kg·m^{-3})	1 810
Thermal expansion coefficient of matrix α_m/K^{-1}	26×10^{-6}
Thermal expansion coefficient of the particles α_p/K^{-1}	4×10^{-6}
Processing temperature T_p/℃	700
Mould temperature T_m/℃	24
Viscosity of melt at 725 ℃ η_{o}/(Pa·s)	0.009 63
Rotation speed n/rev	1 000, 1 200, and 1 500
Angular velocity ω/(rad·s^{-1}) (Rotation speed of 1 000 r/min)	105
Angular velocity ω/(rad·s^{-1}) (Rotation speed of 1 200 r/min)	126
Angular velocity ω/(rad·s^{-1}) (Rotation speed of 1 500 r/min)	157
Solidification rate R at the weight fraction of 5%	0.009
Solidification rate R at the weight fraction of 10%	0.019
Solidification rate R at the weight fraction of 15%	0.029

Fig.3 shows a comparison of experimental and theoretical results for particle concentration in graded composites produced under various process conditions while considering the change in filling radius during the particle displacement. The comparison shows that the theoretical analysis, based on Eq.(13) is sensible. The findings display the effect of the variation in mould rotational speed on the particle concentration from the outer surface to the inner surface. From Fig.3 , it is clear that the deviation between the theoretical and experimental curves decreases in the graded composites reinforced with the weight fractions of 5% and 10% of particles compared with the weight fraction of 15%. Also, Fig.3 depicts the large disparity between theoretical analysis and experimental results of composites produced at 1 200 r/min and the weight fraction of 15%. This disparity could be attributed to the fact that, as previously stated, most theoretical models did not account for the effect of temperature on the dynamic viscosity of the liquid and the solidification rate. This was to be expected because the model assumes that solidification begins as soon as the centrifugal force is applied. Solidification begins a few seconds after the centrifugal force is operated in the experiments, providing the hard particles more opportunity to adopt a more slanted profile within the matrix alloy. Additionally, the model does not account for the amount of superheat in the melt that must be extracted, or the heat transfer conditions of the mold wall, which delays the start of solidification even more. Furthermore, because of the presence of a varying degree of solidification rate with chill distance, assumptions of a constant solidification rate and no interaction between particles and the solid-liquid interface are not always accurate. A similar pattern of results was obtained by other studies[27,31]. Table 2 compares particle concentrations experimentally and theoretically as a function of mold rotational speed and weight fraction at various zones (outer and middle). It is seen that the theoretical model has a lower estimate of the concentration values for the outer and middle zones. The disparity between theoretical and experimental particle concentration is because the models do not consider specific parameters, as previously stated in detail.

As shown in Table 2, The results of the comparison between the theoretical model and experimental results of SiCp distribution in the AZ91 matrix composite showed a difference of 5.83%, 10.20%, and 4.86% in the outer region and 2.64%, 1.58%, and 2.36% in the middle region for each of the weight fractions of 5%, 10%, and 15% composites, respectively.

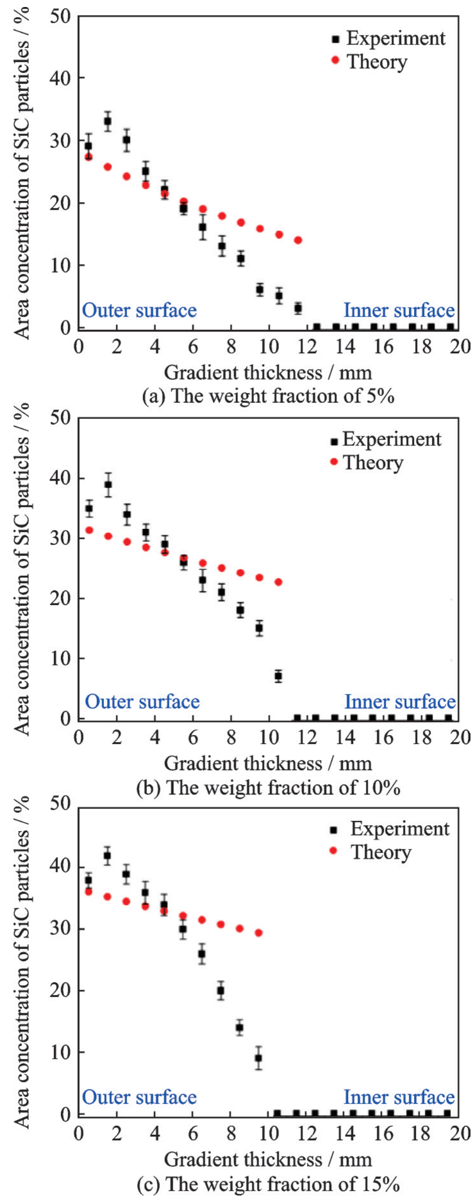


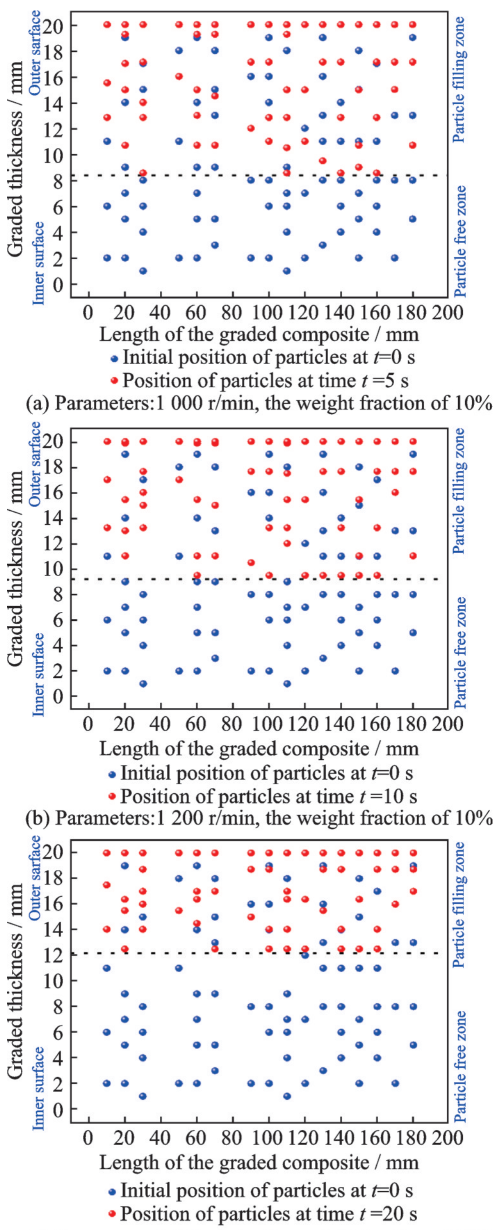
Fig.3 Comparison between theoretical analysis with experimental results of particle concentration along with the thickness of graded composites at 1 200 r/min

Table 2 Experimental and theoretical concentration of particles at different conditions

Mould rotation speed/ ($r \cdot min^{-1}$)	Weight fraction/%	Area concentration of SiC particles at different zones/%			
		Experimental		Theoretical	
		Outer	Middle	Outer	Middle
1 200	5	29	22	27.31	21.42
	10	35	29	31.34	28.54
	15	38	33	36.15	33.78

2.2 Evaluation of particle motion

Fig.4 shows the influence of mold rotation speed on the particle gradient within the graded thickness from the outer surface to the inner surface based on theoretical analysis using Eq.(13). The prior model created by Babu et al.[22] was utilized to identify the initial position of the particles in this analysis. Based on the results, it can be seen that with the increase in the rotation speed of the mold, the particle free zone increases, and the particle concentration on the outer zone increases.



(a) Parameters:1 000 r/min, the weight fraction of 10%

(b) Parameters:1 200 r/min, the weight fraction of 10%

(c) Parameters:1 500 r/min, the weight fraction of 10%

Fig.4 Particle gradient (distribution) patterns obtained from the theoretical model at different speeds

The results indicate that increasing the mold rotational speed leads to a greater extent of inhomogeneity of particle content across the graded thickness of the produced composites. This is primarily due to the fact that with the increase of the rotational speed, the centrifugal force becomes largely sufficient to overcome the other forces and push the particles towards the outer surface of the graded composites. As illustrated, the particle free zone was 8.5 mm at 1 000 r/min, compared with 9.5 mm and 12.5 mm at 1 200 r/min and 1 500 r/min, respectively. These findings suggest that the mold rotational speed has a significant influence on the particle distribution within the graded composites.

Furthermore, the theoretical model proposed in this study is user-friendly and provides a clear visualization of particle movement during the centrifugal casting process, allowing for improvement at any stage of the manufacturing process. These features of the theoretical model make it a valuable tool for optimizing the design and manufacturing of functionally graded magnesium matrix composites. Fig.5 shows the effect of time intervals on the particle position across the graded thickness of the produced composites for four different time intervals of 5, 10, 20, and 40 s. The particle free zone expands as the solidification time increases. As a result, the solidification time is regarded as one of the most important factors influencing the formation of the gradient within the thickness, as a short solidification time results in insufficient distribution of the particles to obtain the required gradient. In contrast, an increase of the solidification time results in the metal solidification before obtaining the required distribution or the aggregation of particles on the outer surface of the produced composites, which leads to the weakness of the matrix. In addition, there was a better agreement between the theoretical results and the trend observed in the experimental results in this work, and a similar pattern of findings was obtained by other studies[16,22].

Fig.6 shows the effect of weight fraction on the particle movement across the graded thickness from the outer surface to the inner surface according to theoretical analysis using Eq.(13). It was observed that as the weight fraction of particles increases, the particle free zone increases. As shown in Fig.6, the particle free zone was 8.5 mm at the weight fraction of 5%, compared with 9.5 mm and 10.5 mm at the

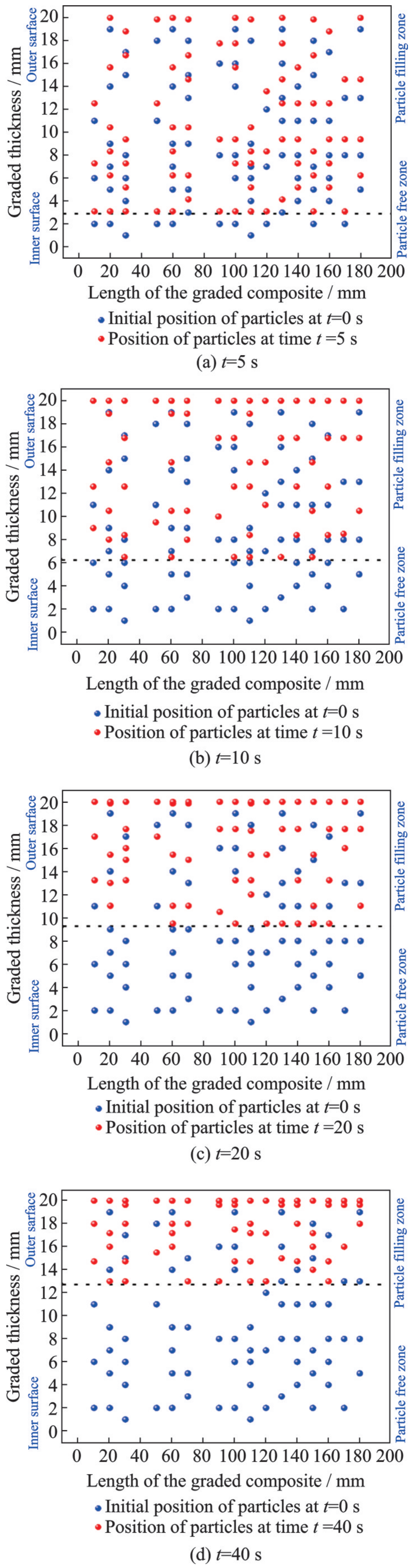


Fig.5 Particle gradient (distribution) patterns at different time

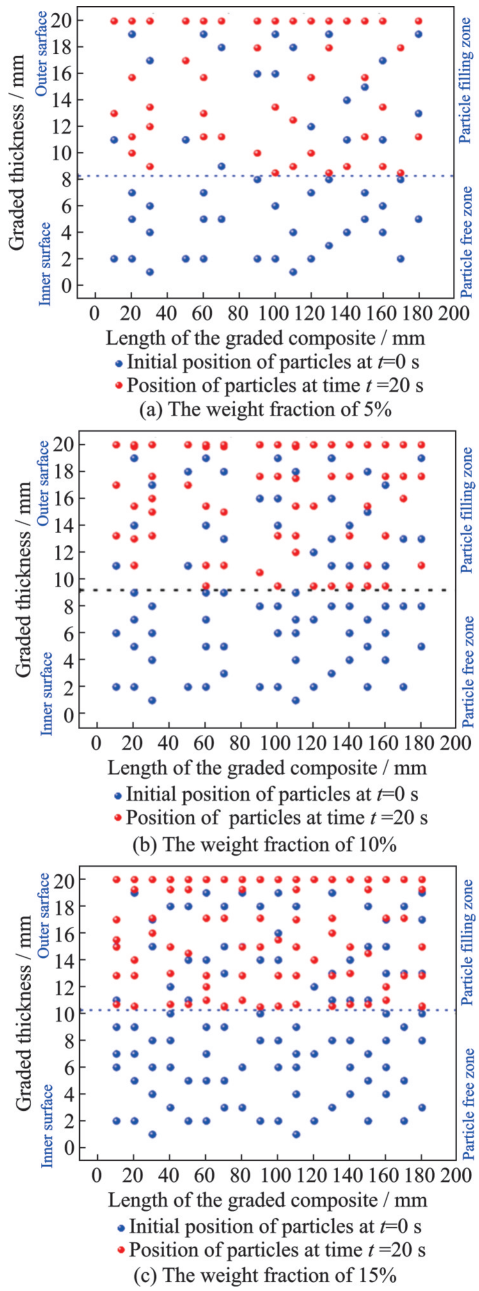


Fig.6 Particle gradient (distribution) patterns obtained from the theoretical model at 1 200 r/min for different weight fractions

weight fractions of 10% and 15%, respectively. Thus, the movement of SiC particles inside the AZ91 matrix alloy is influenced by the initial weight fraction. Furthermore, the solidification time is primarily determined by convection cooling caused by the rotational speed of the mould, and the initial position of the particles in the melt is determined by the type of stirring and the baffles used. As a result, particle size and weight fraction are possible and easily variable parameters. Thus, the gradient or distribution formation process in the graded thickness of the produced composites can be easily controlled by using different particle weight fractions.

The theoretical model proposed in this paper has some limitations and assumptions that may affect its accuracy. For instance, the difference in the results becomes less prominent in the middle zone of the graded composites because of the value of the centrifugal force in this case, which contributes to pushing the particles on the outer surface. Also, the model assumes that solidification begins as soon as the centrifugal force is applied, whereas solidification begins a few seconds after the centrifugal force is operated in the experiments, providing the hard particles more opportunity to adopt a more slanted profile within the matrix alloy. Additionally, the model does not account for the amount of superheat in the melt that must be extracted, or the heat transfer conditions of the mold wall, which delays the start of solidification even more. Moreover, assumptions of a constant solidification rate and no interaction between particles and the solid-liquid interface are not always accurate due to the presence of a varying degree of solidification rate with chill distance. These limitations and assumptions should be taken into account when interpreting the results of the theoretical model and improving the design and manufacture of functionally graded magnesium matrix composites.

3 Conclusions

This paper presents a unique theoretical analysis to explain the mechanism of gradient creation within the thickness during the centrifugal casting of functionally graded magnesium matrix composites. The analysis is divided into two parts: The first part investigates the effect of major parameters such as particle radial velocity, melt viscosity, particle size, and density on particle concentration within the graded thickness, while the second part examines the solidification impacts, along with the other main forces such as the centrifugal force and the drag force, on particle movement under different conditions. The motion of solid reinforcement in a viscous molten Mg alloy under the centrifugal action is considered in this paper. The particle concentration under the centrifugal force is calculated by taking into account the movement of each particle suspended in the molten metal. To test the applicability of the proposed theoretical analysis, the gradient pattern and particle distribution of SiC particles in the AZ91 matrix with graded behavior under different conditions were studied and compared with experimental data reported by other researchers.

The comparison demonstrates that the theoretical model provides an acceptable approximation of the experimental results. Specifically, the difference between the experimental and theoretical results of SiCp distribution in the AZ91 matrix composite was 5.83%, 10.20%, and 4.86% in the outer region and 2.64%, 1.58%, and 2.36% in the middle region for each of the weight fractions of 5%, 10%, and 15% composites, respectively. These findings support the validity of the proposed theoretical analysis. Finally, this study provides valuable insights into the mechanism of gradient creation within the thickness during the centrifugal casting of functionally graded magnesium matrix composites. The proposed theoretical analysis can be used to optimize the design and manufacture of such composites for various industrial applications.

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Author Dr. **SALEH Bassiouny** received his B.S. and M.S. degrees from Alexandria University (AlexU), Alexandria, Egypt in 2012 and 2017, respectively. He completed his Ph.D. degree in engineering mechanics from the College of Mechanics and Materials, Hohai University (HHU), Nanjing, China, in 2021, and has accumulated more than ten years of research background in material science and technology. Currently, he serves as a postdoctoral researcher at Nanjing University of Aeronautics and Astronautics (NUAA), where his current research interests focus on functionally graded materials, metal matrix composites, additive manufacturing, equal-channel angular pressing, wear, casting, and corrosion analysis.

Author contributions Dr. **SALEH Bassiouny** and Ms. **FATHI Reham** designed the study, performed the experiments, conducted the analysis, interpreted the results, and wrote the manuscript. Dr. **ABDALLA Modawy Adam Ali** and Dr. **SHANKAR Karthik V** contributed to the discussion and background of the study. Prof. **RADHIKA N** conducted the analysis, interpreted the results, revised and modified the manuscript. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

离心铸造梯度镁复合材料中颗粒分离的理论研究

SALEH Bassiouny[1,2], FATHI Reham[3], ABDALLA Modawy Adam Ali[4], SHANKAR Karthik V[5], RADHIKA N[6]

(1.南京航空航天大学能源与动力学院, 南京 210016, 中国; 2.Production Engineering Department, Alexandria University, Alexandria 21544, Egypt; 3.南京航空航天大学机电学院, 南京 210016, 中国; 4.河海大学能源与电气学院, 南京 211100, 中国; 5.Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amritapuri 690525, India; 6.Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Coimbatore 641112, India)

摘要:使用理论和实验研究探究主要参数对离心铸造镁基复合材料中颗粒分布的影响。旨在描绘凝固对颗粒运动的影响,以及其他主要力量。研究结果表明,旋转速度、凝固间隔和基体与颗粒之间的密度差异会影响由离心力引起的颗粒分离区域的厚度。此外,对AZ91基体复合材料中SiC颗粒分布的理论模型和实验的比较表明,在中部区域10%(重量百分比)的分布分析是可接受的。对于每个5%、10%和15%(重量百分比)复合材料,实验和理论结果之间的差异分别为外部区域的5.83%、10.20%和4.86%,中部区域的2.64%、1.58%和2.36%。

关键词:梯度材料;理论分析;离心力;AZ91合金;颗粒分离