Review Article

Particle Dynamics in Metal Matrix Composites – A Review

Vishal Mehta[1*], Mayur Sutaria[2]

[1,2]Department of Mechanical Engineering, C. S. Patel Institute of Technology, Charotar University of Science and Technology, Changa. Gujarat. India

Received: 24/02/2017
Revised: 10/07/2017
Accepted: 10/07/2017

Correspondence to:
*Mehta Vishal:
vishalmehta.me@charusat.ac.in

Abstract:

Metal Matrix Composite (MMC) denotes to composite structure which is based on metal or alloy substrate, united with metallic or non-metallic reinforcements. The objective of developing composite materials is to conglomerate required features of metal and reinforcement. The fabrication of MMC through the processing of casting comprises the interaction of solidifying front (solid-liquid interface) with reinforcement particles. Usually dendritic/cellular crystal evolution is involved in processing stage and these crystals react with the surrounded reinforcement particles to produce the end product. In this way, complex crystal evolution phenomena joined with the dynamics of the particles characterizes the microstructure and finally the execution of the composite. This paper presents the review on different phenomena involved in particle dynamics and their influence during manufacturing of metal matrix composites.

Keywords: Critical Velocity, Metal Matrix Composites (MMC), Particle Dynamics, Solid-Liquid Interface, Solidification Front

INTRODUCTION

In the context of MMCs, particle dynamics basically refer to collaboration between reinforcement particle and solid-liquid (SL) interface. It contains pushing and/or engulfment activities of particle with reference to SL interface, understating a 'critical velocity' phenomena and force balance system of Metal Matrix Composites (MMC).

The phenomenon of association of particles with solid-liquid interfaces has been examined since mid-1960. While the first consideration reduced from topography applications (components of soil), scientists soon perceived that understanding particle execution at solidifying interfaces may create valuable guides in different sectors, metallurgy is one of them. The matter is the position of particles regarding grain limits toward the finish of solidification. Impressive measure of test and hypothetical research was centered around applications to MMC fabricated by metal shaping method (Stefanescu, 2009).

The particle measurements of concern are more often in the micron run. In this way, the measure of particles is relative through the span sizes of common dendritic/cell crystal-like structure. Such particles can cooperate in various means with a moving toward solidifying front; it might be: (a) pressed by the travelling front, (b) immersed in front, or (c) pressed for some time formerly engulfed or captured among coming dendrite arms. In a MMC, the composite properties are relay on the association of the particles in the liquid metal (Ferguson et al., 2014). Understanding the particle–front connection marvel is key for affecting unrivaled control of the scrambling of particles in composite. In the event that the particles are consistently disseminated, will accomplish the favored quality and wear safe characteristics than if the particles are scattered or bunched in neighborhoods. On the whole, pushing of particle by the front is unfavorable and may prompt particle consumption /aggregation in particular sections of the solidified metal (Rohatgi, 1993).

During solidification process when a solidification front reaches near to particle, repulsive disjoining pressures in melt film turn out to be substantial and make the particle travel. Furthermore, the movement of the particle strain the liquid into gap and make a drag force which is as opposed to separating pressure (for the repulsive van der Waals interface between the surfaces) and the harmony amongst the drag force F_D and the separating pressure force F_I chooses the general particle dynamics (as shown in Fig. 1), i.e. whether the particle will observe pushing or engulfment by the propelling front (Udaykumar et al., 1999; Garvin and Udaykumar, 2006).

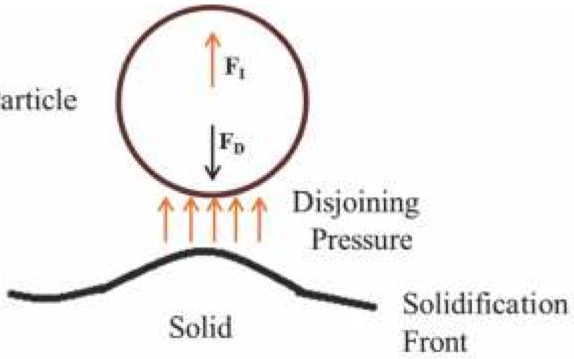

Fig. 1: Schematic of the different mechanisms involved in the particle–solidification front interaction

As discussed above interaction of particle with solid-liquid interface is important phenomenon. Research carried out by different researchers' has been reviewed and discussed in the following section.

MODELING OF CRITICAL VELOCITY

Behavior of particles in MMC is governed by communication between particle and solid-liquid (SL) interface. Such behavior is analyzed by various forces involved in a system of particle and SL interface. For such studies different models presented by researchers are discussed in following section.

Uhlmann et al., (1964) have viewed the critical velocity as arising from instability occurred during pushing phenomena. They observed that if velocity of particle is lower than critical velocity, particles are rejected by the interface and if velocity of particle is beyond critical velocity, particles are trapped in the solid. Authors have developed a theory established on the hypothesis that little scope of shock exists between the particle and the solid. This repulsion happens when the particle-solid interfacial free energy is superior to totality of particle-liquid and liquid-solid interfacial free energies. They have investigated necessity of the critical velocity on numerous properties of matrix and particle. The critical velocity for small particles (below 15 µ in diameters) was observed to be independent of the size of the particles. For particles hundreds of microns in diameter, the critical velocity was found to be lesser for larger particles. Critical velocity is normally greater in matrix materials of lower viscosity. They also proposed model to account critical velocity as shown in Eq. (1).

$$Vc = \frac{(n+1)}{2}\frac{La_0V_0D}{BTR^2} \qquad (1)$$

Where, D the diffusion coefficient for matrix liquid in the section between particle and solid; B Boltzman's constant; T the temperature; V_0 the atomic volume; R the particle radius, L is the latent heat per unit volume; n the positive number of order 4 or 5.

Shangguan et al., (1992) proposed an analytical model for the interface between an insoluble particle and a proceeding solid-liquid interface. An examination was executed keeping in mind the end goal to know the dynamics of an proceeding solid-liquid interface behind a particle as well as the behavior of the particle in front of the particle boundary interaction. (Schematic diagram of communication between particle and solid-liquid interface is shown in Fig. 2) There is a critical velocity for the pushing /engulfment changeover of particles by the boundary. The critical velocity was found to be material parameters and processing variables dependent, such as viscosity of melt, wettability between the particle and the matrix, thermal conductivity ratio, and the size of particle. The essentialness of the review on the handling of particle reinforced MMCs (Al/SiC) was discussed, and strategies for observing particle distribution in MMC was mentioned. Investigation examined in this review included the resolving temperature field for the particle/matrix configuration, figuring the state of the solid-liquid boundary in the locality of the particle, calculating the forces acting on the particle, establishing the basic circumstance for the pushing/engulfment transition. Model proposed expression of critical velocity V_c is:

$$Vc = \frac{\Delta\beta a_0}{12\eta\alpha R} \qquad (2)$$

Where, a_0 is atomic distance, α is thermal conductivity ratio, η is viscosity of melt, R is particle radius and $\Delta\beta$ is interfacial energy.

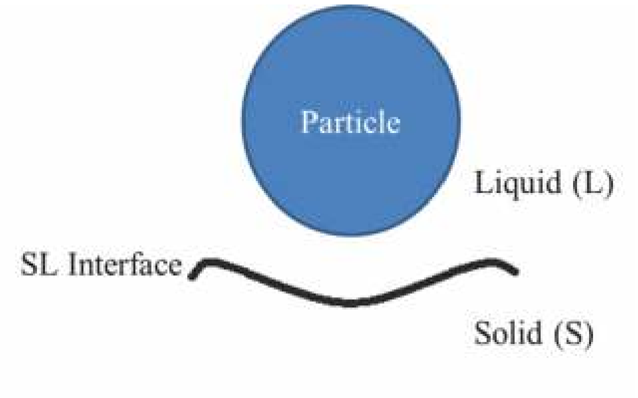

Fig. 2: Schematic diagram showing a particle in front of the solid-liquid (SL) interface

Kim & Rohatgi, (1998) presented an model for particles and propelling SL interfaces during solidification of pure melts where the shape and the curvature of the SL interface behind the particle was conveyed on basis of the proportion of thermal conductivity of the particle to the melt, the viscosity of melt, the surface tension of SL interface, the heat of fusion of melt, and the temperature gradient executed on the SL interface. The critical velocity of the SL interface behind the particle moving near the SL interface under consistent state conditions is:

$$Vc = \frac{\Delta\sigma\,(kR+1)a_0}{18\eta R} \qquad (3)$$

Where, k is curvature thickness, ρ is density, η is viscosity of melt, $\Delta\sigma$ is difference in surface energy.

Catalina et al., (2000) built up a scientific model to look at a particle and an advancing solidification front communication. A viscosity was assumed to be steady in the gap amongst the particle and the front (SL interface) to a film thickness of $7a_o$ (a_0 is atomic diameter). Based on numerical estimation an expression for the drag force, was utilized as opposed to an analytical expression. The model characterizes the particle-front interaction. It shows that this cooperation is essentially at non-consistent state and that steady state finally follows only when the solidification is conducted at sub-critical velocities. SL Interface considered for the modeling is as shown in Fig. 4.

Where, R_p Particle radius, RI position of SLI with respect to the center of particle, V_p velocity of particle, V_t velocity of the tip of the SLI, VS solidification velocity, θ angle in spherical coordinates, L distance among the focal point of the particle and the unperturbed SLI, d distance between the particle and the solid-liquid interface.

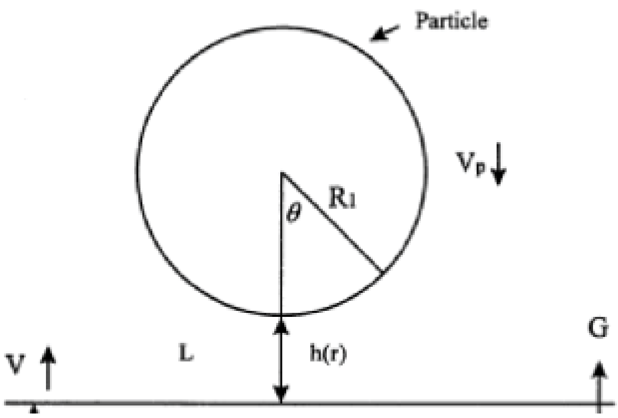

Fig. 3: Particle ahead of solid-liquid (SL) interface [Kim & Rohatgi, (1998)]

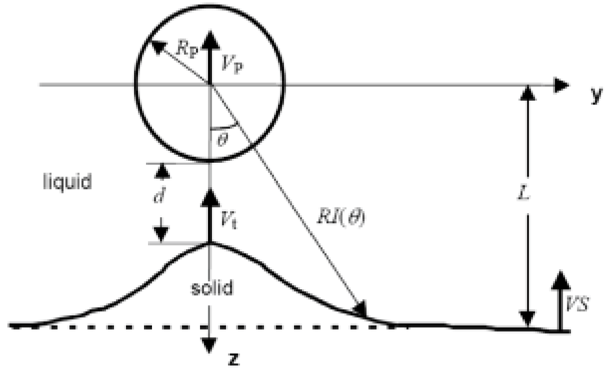

Fig. 4: SL interface in the existence of a foreign particle ($K_P < K_L$) [Catalina et al., (2000)]

Garvin & Udaykumar, (2003a) have performed simulations of interface of fronts with particles by ascertaining the front transmission and consolidating the solidification procedure to the particle movement. Such consolidated iterations, i.e. together with the mutual effect of the particle and the solidification process at every time stage, have not been executed earlier. A dynamic model was based on impact of repulsive and attractive forces. The outcomes achieved from the phase change combining with the embedded dynamic force calculation were then contrasted with the consequences gained from the semi-analytical dynamic model. They observed the tip velocity of the semi-analytical estimation was considerably higher than that for the consolidated computation.

Garvin & Udaykumar, (2003b) have studied the collaboration of a front with particle by methods for numerical simulations to join phase change with particle movement. The particle transports under the effect of forces that act through the space between it and the evolving solidification front. They observed that the critical velocity either depend on cut-off value of the gap thickness or the critical velocity is compares to zero gap thickness.

Fras & Olejnik, (2008) determined critical velocity for two composites succinonitriale-polystyrene (K1) and succinonitriale-glass (K2) composite. The forces acting on a particle have been examined to understand phenomena of particle solidification front interaction. Using a force balance system they derive an equation for the critical velocity as:

$$Vc = \frac{\Delta\sigma a_0}{3R\gamma\eta} \qquad (4)$$

Where, *R* is radius of particle and is dimensionless coefficient. They have concluded that, depending on the particles size and velocity of the solidification front movement, the front can be either active or neutral in respect of the composite particles. Active solidification front by pushing the particles favours the formation of clusters, which cause microstructural heterogeneities in composite. With neutral solidification front, particles are engulfed which causes the microstructural homogeneities. They also concluded that, neutral-active change of a given size takes place at a critical velocity.

RATIO OF THERMAL CONDUCTIVITY

The ratio of thermal conductivity of particle to the liquid melt (k_p/k_l) plays chief role in acknowledging the shape of SL interface and finally particle dynamics.

Garvin et al., (2007a) developed way to deal with examine the communication in the midst of a propelling front and particle in the melt. The limits in the issue are followed by methods for a level-set strategy and a cartesian lattice based sharp interface technique is utilized to register the overseeing conditions in the presence of the moving interfaces. There are two computational areas, the aggregate particle-front system and the thin gap between the front and the particle. The dynamics of the fluid, phase boundary and particle in this area impacts the particle dynamics.

It was observed that at or close to the critical velocity the framework is genuinely touchy to agitations either bringing about engulfment or pushing. This is attributable to the mind boggling connection between the interface shape created because of ratio of thermal conductivity of the particle to the melt, k_p/k_l and premelting effects, also due to inter-molecular repulsive forces and drag forces. As long as a premelted layer is assumed to exist between the particle and the front, a particle drawing near to solidification front of a pure material will become engulfed when $k_p/k_l \geq 1.0$. The velocity equals to the critical velocity for particle engulfment, is normally obtained from the consolidated dynamics [Garvin et al. (2007b)].

Agaliotis et al., (2012) presented a model of the effect of interface shape on particle pushing using an axisymmetric estimate applied to define the influence of various parameters like radius of particle, velocity of interface and shape of interface on the expected critical velocity for engulfment of the particle by the solidifying interface. The model was valuable to conditions which create planar, concave and convex interface shapes acquired by presenting in the model melt particles with various thermal conductivity ratio k_p/k_l of 1, 10 and 0.1 where two forces were considered: drag force and the repulsive force. The parting distance among particle and interface approaches a minimum value of 10^{-8} m, the trapping condition is applied. Concave or convex interface shapes are obtained, respectively for outside particles with bigger or smaller thermal conductivities than that of the matrix. They concluded that for divisions larger than a particle diameter there is no influence on interface shape.

Zubko et al., (1973) studied effect of thermal conductivity ratio (k_p/k_l) on particle dynamics in various MMC. They observed that in MMCs like Zn comprising W particles, Bi comprising W and Ta particles, and Sn comprising W and Mo particles, particles was engulfed by SL interface due to $k_p/k_l < 1$. Whereas in MMCs like Zn comprising Ta particles and Sn comprising Ta particles, particles was pushed by SL interface due to $k_p/k_l > 1$. Kim & Rohatgi, (1998) have observed the $k_p/k_l < 1$in Al-SiC MMC resulting in particle pushing by SL interface. Agaliotis et al., (2012) witnessed $k_p/k_l < 1$in Zn-Al_2o_3 and Al-Tio_2 MMC resulting in particle pushing. These remarks credibly revealed the importance of the thermal conductivity ratio in the particle pushing/engulfment transition and finally on particle dynamics.

EFFECT OF PARTICLE SIZE ON PARTICLE DYNAMICS

The size of reinforcement particle is varying from micro to nano scale range. The size of particle is influencing on critical velocity and ultimately on particle dynamics. Amount of critical velocities are different as particle size differs.

Uhlmann et al., (1964) have studied the dependence of particle size on critical velocity. The critical velocity for small particles (below 15 μ in diameters) was observed to be independent of the size of the particles. For particles having diameter in range of hundreds of microns, the critical velocity was observed to be lesser for larger particles. In this large size range, the critical velocity was found to be shape dependent as well, being smaller for flatter faces presented by the particle to the interface. Solid particles with irregularities are expected to have higher critical velocities in a given matrix than smooth particles of the same size. For rough particles, the interaction with the interface takes place over several irregularities. Their effect is to make easier liquid transport to the region of contact. For smooth particles, a $1/R^2$ size dependence of the critical velocity is anticipated. For rough particles, the size dependence arises from the viscous drag term, and becomes effective only for large particles. In the range of particle sizes greater than 100μ, this dependence should be proportional to $1/R^{1/2}$ assuming the average irregularity size to be independent of R (particle radius).

The models mentioning the interaction amongst particle and SL interface envisage that large size particles will be engulfed by SL interface while smaller particles containing nanoparticles will be pushed by it. However, sometimes nanoparticles can be engulfed and disseminated through the material. This disparity was studied by Ferguson et al., (2014) considering the Brownian motion effects on particle. They have identified two mechanisms for capture of the particles. In capture I mode, big jumps permit the particle to reduce the repulsion of the solidification front, and the e ect of Brownian motion is essentially to enhance the drag force. On the other hand, in Capture II mode, the total force acting on the particle is insu cient to accelerate the particle to a velocity high enough to beat the progressing SF. The e ect of reinforcement particle size on the steady state or critical velocity of the SF was examined and showed that this velocity is lowered when the e ects of Brownian motion are taken into consideration. There is a small decrease for extremely small Nano Particles-NPs (i.e., less than 3 nm), a large decrease for particles in small NPs (i.e., 3 to 8 nm), and no change for larger NPs (i.e., above 9 nm) for the Al/Al_2O_3 MMNC system.

Szucki et al., (2015) presented particle interactions with the moving front during a solidification of the metal matrix composite. An investigation was made for SiC particles and ZnAl compound in aluminum. They have observed that, calculations of the gravity force influencing the SiC particle in the locality of the crystallization front effects to higher degree particles of larger sizes. The difference of density among a particle and matrix equivalents to 3359 kg/m^3 for ZnAl8/SiC composite, whereas this difference is excessively lower (1544 kg/m^3) for ZnAl27/SiC composite. In case of particles radiuses of order of 10^{-4} m, the gravity force is by one order of magnitude lower for ZnAl27 alloy in contrast with ZnAl8 alloy. The computation for small particles showed that the density of matrix did not affect expressively on the gravity force. It was found that the drag force acts in an advanced degree on large particles near to crystallization front and transporting with a higher velocity. An increment in viscosity was found as a temperature decreases at time of solidification. Also the higher percentage of SiC particles will leads to increment in viscosity.

EXPERIMENTAL ANALYSIS OF PARTICLE DYNAMICS

Present section discusses the experimental investigation carried out to understand particle dynamics.

Hanumanth et al., (1992) studied the particle sedimentation during preparation of liquid metal-matrix composites. At the stage of solidification, sedimentation will take place, which will change the volume fraction of particles. In their study, volume fraction of reinforcement particles in the A356 molten metal was connected to calculation of sedimentation rates of 90 μm diameter silicon carbide particles in molten aluminum. The outcomes designate that the rate potentially depends on volume fraction, the time to clarify a 0.15m depth increased from nearly 60 to 500 seconds as the particle volume fraction expanded from 0.05 to 0.30.

Youssef et al., (2005) explored the conduct of titanium diboride particles in liquid aluminum by performing casting experiments at varying cooling rates and particle addition levels, initializing with a master alloy comprising in situ formed TiB_2 particles. Commercial purity aluminium and an Al-4% Mg (A514) alloy were chosen for the study. The critical velocity was evaluated for Al-TiB2 composite. The outcomes were confirmed against the estimates of the models available in the literature. At low particle concentration, the critical velocity observed in Al composite was among 4 and 8 μm/s and reaches near to 2μm/s as the particles reinforcement increases. In the case of A514, at the low particle concentration the critical velocity was lower (between 2 and 3 μm/s).

Fras & Olejnik, (2008) have performed experiments on Succinonitriale-polystyrene using polystyrene particles of the radius R: 3, 6, 10, 15,100 μm (K1) and succinonitriale-glass with glass particles of radius R: 5.4, 12, 24, 38.9, 41, 49 μm (K2) composite. Critical velocities of these composites were determined experimentally. They observed the critical velocity for composite K1 were ranging from 0.096 to 2.60 μm/s and for composite K2 was between 0.073 to 0.650 μm/s. also amount of critical velocity was increases with increase in particle radius.

For Al/SiC MMC available models for critical velocity predicts that critical velocities were from 0.187 to 5800 μm/s. But experimentally observed critical velocities were in the range from 13,100 to 15,600 μm/s [Kim & Rohatgi, (1998); Ferguson et al., (2014)].

It is critical to select the best available model for the given material system. Nevertheless, it is expected that any of these models may be modified using the method of integrating Brownian motion and thus enable the prediction of particle pushing and/or engulfment Ferguson et al., (2014).

SUMMARY

A survey of research was carried out to know the performance of particles with solid-liquid (SL) interface and ultimately particle dynamics. Studies on interaction between particle and SL interface, effect of particle size on dynamics, critical velocity, and particle pushing-engulfment phenomena was presented in this paper.

The most of available theories discussed about particle dynamics, are based on planer solid-liquid (SL) interface. Whereas, general solidification process during casting process involves concave and convex shape of interface for variety of cast geometries. Different region inside cast geometry has variety of concave and/or convex shape of SL interface, as heat transfer rate from the boundaries are different. This will influence the particle dynamics during processing of MMCs and finally microstructure as well as performance of the composites. Further investigations may be directed towards the effect of part geometry or shape of mold cavity on particle dynamics of metal composites.

REFERENCES

1. Agaliotis, E. M., Schvezov, C. E., and Rosenberger, M. R. (2012), "A Numerical Model Study of the Effect of Interface Shape on Particle Pushing," Journal of Crystal Growth, Vol 354, pp. 49-56.

2. Catalina, A. V., Mukherjee, S. & Stefanescu, D. (2000), "A Dynamic Model for the Interaction between A Solid Particle and An Advancing Solid/Liquid Interface", Metallurgical and Materials Transactions A, Vol 31, pp. 2559-2568.

3. Ferguson, J.B., Kaptay G., Schultz B. F., Rohatgi P. K., CHO K., Kim C. (2014), "Brownian Motion Effects on Particle Pushing and Engulfment During Solidification in Metal-Matrix Composites". Metallurgical and Materials Transactions A, Vol 45, pp.4635–4645.

4. Fras, E. and Olejnik, E. (2008), "Interaction between solidification front and alien phase particles". Archives of Metallurgy and Materials, Vol 53, pp.695-702.

5. Garvin, J.W. & Udaykumar, H.S. (2003a), "Particle-Solidification Front Dynamics Using A Fully Coupled Approach, Part I: Methodology". Journal of Crystal Growth, Vol 252, pp.451–466.

6. Garvin, J.W. & Udaykumar, H.S. (2003b), "Particle-Solidification Front Dynamics Using A Fully Coupled Approach, part II: Comparison of Drag Expressions". Journal of Crystal Growth, Vol 252, pp.467–479.

7. Garvin, J.W., Yang, Y. & Udaykumar, H.S. (2007a), "Multiscale Modeling of Particle-Solidification Front Dynamics, Part I: Methodology". International Journal of Heat and Mass Transfer, Vol 50, pp.2952–2968.

8. Garvin, J.W., Yang, Y. & Udaykumar, H.S. (2007b), "Multiscale Modeling of Particle-Solidification Front Dynamics. Part II: Pushing-Engulfment Transition". International Journal of Heat and Mass Transfer, Vol 50, pp.2969–2980.

9. Hanumanth, G.S., Irons, G. a. & Lafreniere, S. (1992), "Particle Sedimentation During Processing of Liquid Metal-Matrix Composites". Metallurgical Transactions B, Vol 23, pp.753–763.

10. Kim, J.K. & Rohatgi, P.K. (1998), "An Analytical Solution of The Critical Interface Velocity for The Encapturing of Insoluble Particles by A Moving Solid/Liquid Interface". Metallurgical and Materials Transactions A, Vol 29, pp.351–358.

11. Kim, J.K., and Rohatgi, P.K. (1998), "The Effect of the Diffusion of Solute Between the Particle and the Interface on the Particle Pushing Phenomena," Acta Materialia, Vol 46, pp. 1115-1123.

12. Rohatgi, P.K. (1993), "Metal-Matrix Composites", Defense Science Journal, Vol 43, pp. 323-349.

13. Shangguan, D., Ahuja, S. & Stefanescu, D.M. (1992), "An Analytical Model For The Interaction Between An Insoluble Particle And An Advancing

Solid/Liquid Interface". Metallurgical Transactions A, Vol 23, pp.669–680.

14. Stefanescu, D.M. (2009), "Science and Engineering of Casting Solidification," Second edition, Springer, New York.

15. Szucki, M., Kalisz, D., Lelito, J., Zak, P.L., Suchy, J.S. and Krajewski, K.W. (2015), "Modelling of The Crystallization Front–Particles Interactions In ZnAl/(SiC)p Composites". Metalurgija, Vol 54, pp.375-378.

16. Uhlmann, D.R., Chalmers, B. and Jackson, K.A. (1964), "Interaction between Particles and a Solid-Liquid Interface". Journal of Applied Physics, Vol 35, pp.2986-2993.

17. Udaykumar, H.S., Mittal, R. and Shyy, W. (1999), "Computation of Solid–Liquid Phase Fronts In The Sharp Interface Limit on Fixed Grids." Journal of computational physics, Vol 153, pp.535-574.

18. Youssef, Y.M., Dashwood, R.J. and Lee, P.D. (2005), "Effect of Clustering on Particle Pushing and Solidification Behavior in Tib2 Reinforced Aluminium PMMCs." Composites Part A: Applied Science and Manufacturing, Vol 36, pp.747-763.

19. Zubko, A.M., Lobanov, V.G. and Nikonova, V.V. (1973), "Reaction of foreign particles with a crystallization front." Sov. Phys.-Crystallogr., Vol. 18, pp.239-241.