Further Expositions on Semi-Solid Microstructure

Adeleke V. Adedayo[1,2] and Abraham A. Adeleke[1]

[1]Department of Materials Science and Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria
[2]Department of Metallurgical Engineering, Kwara State Polytechnic, PMB 1375, Ilorin, Nigeria

E-mail: adelekeonline@yahoo.com

ABSTRACT

While Semi Solid Metallurgy (SSM) is already a viable manufacturing method, it is still under intensive development, and new critical breakthroughs are still expected. Merton C. Flemings, the founder of semi solid metallurgy, identified the path forward to achieving the much expected breakthroughs. He identified these to be in some key research directions which include the formulation of better understanding of the mechanism whereby desired microstructure for SSM forms. Development and full application of mathematical models as related to SSM are also seen to be very vital. In this present paper, theoretical expositions are made on the effects of intermetallics on microstructure in SSM. The influence of temperature during thixocasting on the SSM structure is also mathematically elucidated.

(Keywords: semi solid metallurgy, globule, microstructure, thixocasting)

INTRODUCTION

Although SSM is already a viable manufacturing method, it is still under intensive development and critical breakthroughs are still expected (Czerwinski, 2008; Fleming, 2011). The production of SSM feedstock is of considerable interest and current research effort is concentrated on production of feedstock alloys where the primary phase in the microstructure consists of globularized particles (Reisi and Niroumand, 2008; Paes et al., 2006; Margarido and Robert, 2003). In general, microstructure affects materials properties (Araoyinbo, 2010).

Whatever the route employed for SSM, several advantages of the process are clear (Fleming, 2000, Adedayo, 2011a, b). SSM employs reduced temperature when compared to the casting of superheated melts. The generally accepted advantages of hardware performance and energy economy, achieved due to reduced operating temperatures are universally positive for all alloys (Czerwinski, 2008), and includes the following: lower energy consumption, no handling of liquid metal, longer die life, better yield from the raw material due to lower oxidation and evaporation, and fewer other losses related to melt overheating.

Aside from the major efforts that will certainly take place in overall process development, Fleming (2000 and 2011), the Toyota Emeritus Professor of Materials Science and Engineering at Massachusetts Institute of Technology (MIT) identifies some key research directions as the path forward for SSM. Foremost of the key research directions is formulation of better understanding of the mechanism whereby the desired SSM microstructure is formed. Also, the development and full application of mathematical models relevant to SSM would be a very vital tool in this quest.

This work is in furtherance of earlier works by Adedayo (2011 a, b). In this present work, theoretical expositions are made on some important features of microstructure of the SSM component. The understanding of the theories of evolution of required microstructure is vital and useful for SSM process designs and other engineering applications. This will also provide insight on fundamentals for achieving the much expected critical breakthroughs in SSM.

INTERMETALLICS AND GLOBULAR MORPHOLOGY

For alloy materials, when the grain boundary grooving occurs such that the boundary intersects the liquid-solid interface, the curvature in the neighborhood of the groove is determined by the

requirement that (Fleming, 1974):

$$T^* = T_m - G\Delta X = T_m - \Delta T_r \quad \textbf{(1)}$$

where T* is the liquid-solid interface temperature, G is the thermal gradient, and ΔX is the distance back from the isotherm at T_m, the equilibrium melting point of the alloy material (the liquidus temperature).

But also, $\Delta G_L = S_L \Delta T_r$ **(2)**

$$\Delta G_s = S_s \Delta T_r + 2V_s \sigma\lambda \quad \textbf{(3)}$$

where ΔG_L and ΔG_s are the changes in free energies of liquid and solid, respectively. V_s is the volume of the solid, λ is the surface curvature in the groove neighborhood, T_r is the decrease in equilibrium melting point, σ is the surface energy of the interface. Assuming that σ is isotropic and does not change as surface area changes, at equilibrium (Fleming, 1974):

$$\Delta G_L = \Delta G_s \quad \textbf{(4)}$$

It follows that:

$$S_L \Delta T_r = S_s \Delta T_r + 2V_s \sigma\lambda \quad \textbf{(5)}$$

$$(S_L - S_s)\Delta T_r = 2V_s \sigma\lambda \quad \textbf{(6)}$$

$$S_L - S_s = -\Delta S \quad \textbf{(7)}$$

$$\Delta T_r = \frac{2V_s \sigma\lambda}{\Delta S} \quad \textbf{(8)}$$

$$\Delta S = \frac{\Delta H}{T_m} \quad \textbf{(9)}$$

$$\Delta T_r = \frac{-2T_m V_s \sigma\lambda}{\Delta H} \quad \textbf{(10)}$$

But: $\Delta T_r = G\Delta X$ **(11)**

$$G\Delta X = \frac{-2T_m V_s \sigma\lambda}{\Delta H} \quad \textbf{(12)}$$

Thus, the relationship between curvature λ and surface energy σ of the interface can be expressed by Equation 12.

However, for a multi-component surface, the resultant surface energy will depend on crystallographic orientation and the surface energies of the constituent components. The resultant surface energy may be evaluated using Cassie equation:

$$\text{Cos } \theta = f_1 \text{Cos } \theta_1 + f_2 \text{Cos } \theta_2 + \ldots\ldots f_i \text{ Cos } \theta i \quad \textbf{(13)}$$

(Adedayo et al, 2010; Adedayo, 2010; MIT, 2009)

i.e $\text{Cos } \theta = \sum f_i \text{ Cos } \theta_i$ **(14)**

where Cosθ is proportional to the resultant surface energy, f_i is the fraction of component i and θ_i is the contact angle of component i. Therefore:

$$\sigma = \sum f_i \sigma_i \quad \textbf{(15)}$$

Therefore;

$$1/\lambda = r = -(2T_m V_s / G\Delta X\Delta H) \sum f_i \sigma_i \quad \textbf{(16)}$$

This shows the dependence of r and hence λ on

$$\sum f_i \sigma_i \quad \textbf{(17)}$$

FORMULATION FOR PREDICTING COMPOSITION OF A GLOBULE

SSM is feasible only with alloys because there exists a MUSHY zone in their phase diagram. Generally, alloys are systems containing two or more different elements. In the slurry zone the constituents of alloys may react to form intermetallics and eutectics. Actually, the reacting species in the alloys are in a balance with the products of reaction because a sort of equilibria is established within the system. Also, in the mushy (slurry) zone, there is a balance between the solid and the liquid phases of the alloy present. This leads to solute redistribution between the solid and the liquid and thus varied compositions of the solid and the liquid. At temperature T, a general material balance (conserving solute atoms) is written:

$$c_s f_s + c_L f_L = C_0 \quad \textbf{(18)}$$

where f_s and f_L are weight fractions of solid and liquid, respectively. C_s and C_L are the solid compositions respectively. C_0 is the initial composition of the alloy. At temperature T, solid of composition Cs is freezing from liquid of composition C_L. A quantitative expression is easily obtained by equating the solute rejected when a small amount of solid forms with the resulting solute increase in the liquid. This balance is:

$$(C_L - C_s)df_s = (1- f_s)dC_L \quad \textbf{(19)}$$

If;

$$C_s/C_L = k \quad \textbf{(20)}$$

where k is defined as the partition ratio then

$$C_s = kC_L \quad \textbf{(21)}$$

$$dCs/dC_L = k \quad \textbf{(22)}$$

Therefore,

$$dCs = kdC_L \quad \textbf{(23)}$$

Substituting the equilibrium partition ratio and integrating from $C_s = kC_0$ at $f_s = 0$, the composition of the globule at the liquid-solid interface Cs as a function of fraction of solid is given as:

$$\left(\frac{C_S}{k} - C_S\right) df_S = (1 - f_S)\frac{dC_S}{k} \quad \textbf{(24)}$$

$$Cs(1 - k)df_s = (1 - f_s)dC_s \quad \textbf{(25)}$$

$$(1 - k)\frac{df_S}{(1 - f_S)} = \frac{dC_S}{C_S} \quad \textbf{(26)}$$

Integrating from 0 to fs and from kC_0 to Cs:

$$(1 - k)\ln(1 - f_S)\Big|_0^{f_S} = \ln C_S\Big|_{kC_S}^{C_S} \quad \textbf{(27)}$$

Substituting 0 and fs for values of fs and kC_0 and Cs for values of Cs:

$$-(1-k)\ln(1-fs) = \ln Cs - \ln kC_0 \quad \textbf{(28)}$$

$$\ln(1- fs)^{k-1} = \ln Cs/kC_0 \quad \textbf{(29)}$$

$$(1 – fs)^{k-1} = Cs/kC_0 \quad \textbf{(30)}$$

Therefore:

$$C_s = kC_0(1 – f_s)^{k-1} \quad \textbf{(31)}$$

or in terms of liquid composition and fraction liquid:

$$C_L = C_0f_L^{(k-1)} \quad \textbf{(32)}$$

TEMPERATURE AND GLOBULE FRACTION

In metal alloys and other alloys where the liquid-solid interface is close to equilibrium, liquid composition within any given interdendritic space is almost uniform and close to the liquidus line of the phase diagram. This assumes a constant liquidus slope M_L (Figure 1).

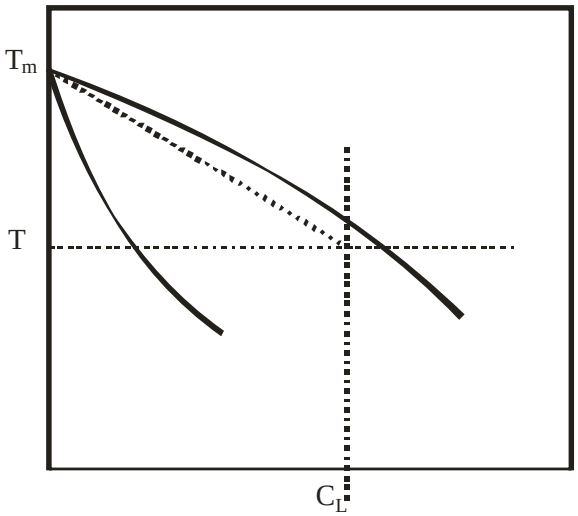

Figure 1: Model of the Liquid-Solid Region.

where T is the temperature of the volume element, T_m is the melting point of the pure solvent metal. Thus:

$$C_L = M_L(T – T_m) \quad \textbf{(33)}$$

But: $C_L = C_0f_L^{k-1}$
where $k = C_s/C_L$ **(34)**

Therefore,

$$M_L(T – T_m) = C_0f_L^{k-1} \quad \textbf{(35)}$$

$$(M_L/C_0)(T - T_m) = f_L^{k-1} \quad \textbf{(36)}$$

Taking logarithm of both sides;

$$\ln[(M_L/C_0)(T - T_m)] = (k-1)\ln f_L \quad \textbf{(37)}$$

$$\ln f_L = [1/(k-1)]\ln[M_L(T - T_m)/C_0]^{(1/(k-1))} \quad \textbf{(38)}$$

$$f_L = (M_L/C_0(T - T_m))^{(1/(k-1))} \quad \textbf{(39)}$$

Globule fraction (solid fraction) is given as:

$$\text{Globule fraction} = f_s \quad \textbf{(40)}$$

$$f_s + f_L = 1 \quad \textbf{(41)}$$

$$f_s = 1 - f_L \quad \textbf{(42)}$$

$$f_s = 1 - (M_L(T-T_m)/C_0)^{(1/(k-1))} \quad \textbf{(43)}$$

The formulation for predicting fraction of a globule is given as:

$$f_s = 1 - (M_L(T-T_m)/C_0)^{(1/(k-1))} \quad \textbf{(44)}$$

CONCLUSION

The theoretical exposition made in this study revealed that globular microstructure of SSM component is dependent on the intermetallics present in the alloy. The role played by temperature on the evolution of globular morphology has also been elucidated. Also, formulation for predicting composition of a globule has been provided.

REFERENCES

1. Adedayo, A.V. 2011a. "Development Processes of Globular Microstructure". *Journal of Mineral, Materials Characterization and Engineering*. 10(7):651-659.

2. Adedayo, A.V. 2011b. "Influence of Furnace Design on Semi Solid Microstructure". *Pacific Journal of Science and Technology*. 12(1):76-79.

3. Adedayo, A.V. 2010. "Effects of Addition of Iron Filings to Green Moulding Sand on the Microstructure of Grey Cast Iron". *Journal of the Brazilian Society for Mechanical Sciences and Engineering*. 32(2):171-175.

4. Adedayo, A.V., O.A. Oyetoyan, S.A. Ibitoye, and A.A. Adeleke. 2010. "Effects of Iron Fillings and Snail Shell on the Properties of Green Moulding Sand". *South Pacific Journal of Natural Science and Engineering*. 28:58-62.

5. Araoyinbo, A.O., M.N. Ahmed-Fauzi, S. Sreekantan, and A. Aziz. 2010. "A Novel Process to Produce Nano Porous Aluminum Oxide Using Alkaline Sodium Phosphate Electrolyte". *Asian Journal of Material Science.* 2:63-68.

6. Czerwinski, F. 2008. "The Basics of Modern SSMP". *Journal of the Minerals, Metals and Materials Society*. 58(6):17-20.

7. Flemings, M.C. 2011. Personal Communications with Merton C. Fleming on Thixocasting in Semi Solid Metallurgy forming process (e-mail correspondence).

8. Flemings, M.C. 2000. "Semi Solid Forming: The Process and the Path Forward". *Metallurgical Science and Technology*. 18(2):3-4.

9. Fleming, M.C. 1974. "Solidification Processing". *Materials Science and Engineering Series*. McGraw-Hill: New York, NY. 162, 273, 286.

10. Margarido, M. and M.H. Robert. 2003. "The Production of Alloys with Rheocast Structure". *Journal of Brazilian Society of Mechanical Science and Engineering*. 25:(2):207-214.

11. MIT. 2009. http://ocw.mit.edu/NR/rdonlyres/Materials-Science-and-Engineering/3-051JSpring-2006/4A278FCF-73A3-4C4C-99A7-81CBC6AE53E5/0/lecture2.pdf. (Page 9)

12. Paes, M., E.G. Santos, and E.J. Zoqui. 2006 "Obtention Rrheocast Structure for Al-4.5wt% Cu Alloy: Comparison Ultra-Refining and Electromagnetic Stirring". *JAMME.* 9(2):21-27.

13. Reisi, M. and B. Niroumand. 2008. "Effects of Stirring Parameters on Rheocast Structure of Al-7.1wt pct Si Alloy. *Journal of Alloys and Compounds*. 32(1):41-47.

SUGGESTED CITATION

Adedayo, A.V. and A.A. Adeleke. 2012. "Further Expositions on Semi-Solid Microstructure". *Pacific Journal of Science and Technology*. 13(1):20-23.

Pacific Journal of Science and Technology