

Influence of Furnace Design on Semi Solid Microstructure.

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ABSTRACT

Semi solid metallurgy offers distinct advantages over other near-net-shape manufacturing processes. Although this process is already a viable manufacturing method, it is still under intensive development and critical breakthrough is still expected. Current research efforts are concentrated towards achieving the much expected breakthrough. In a considerable proportion of published works on the subject, the focus had been on some process parameters. The influence of furnace design of the microstructure of the SSM component has been ignored. This present paper presents a theoretical elucidation on the importance of furnace design on the microstructure of the SSM component.

(Keywords: semi solid metallurgy, manufacturing method, furnace design, microstructure)

INTRODUCTION

Semi-Solid Metallurgy (SSM), sometimes referred to as semi-solid metal processing (SSMP) (Czerwinski, 2008) is an emerging technology with increasing tendency for near-net-shape forming of industrial part, taking advantage of costs reduction and quality improvement (Margarido and Robert, 2003).

Although semi-solid metallurgy is already a viable manufacturing method, it is still under intensive development and critical breakthrough is still expected. To process a material through the semi solid route, all the technologies involved can be divided into two fundamentally different basic routes: rheo-processing and thixo-processing (Czerwinski, 2008). There are also hybrids that combine features of both routes; injection molding is considered to be an example of such hybrids (Czerwinski, 2008).

When utilizing rheo-processing, the starting fully molten precursor is pre-solidified under controlled conditions and then transferred into the mold. The thixo-route involves two stages: first, billet preparation which consists, in fact, of a portion of the rheo-route and, second, billet re-heating and component forming. In general, the key microstructural change, observed after slurry's solidification, is a replacement of dendritic forms by globular morphologies. The understanding of the relationship between a component's integrity and microstructure is vital. The influence of the process parameters on the evolved microstructure is equally important.

In considerable proportion of published works on the effects of process parameters on the evolved microstructure of the semi solid components, the focus had been on parameters such as: processing temperature (Oblak and Rand, 1976), chemical composition of the alloy (Oblak and Rand, 1976; Liu et al., 2003), stirring period (Reisi and Niroumand, 2008), type and concentration of modifiers (Liu et al., 2003), method of slurry production (Margarido and Robert, 2003; Paes et al., 2006; Browne et al., 2003). Little has been done on the role played by furnace design on the characteristics of the evolved microstructure.

In this present work, elucidation is made on the significance of furnace design on some important features of the microstructure of the semi solid components.

OVERVIEW OF GLOBULAR MICROSTRUCTURE ASSESSMENT PROCEDURES

It is a common practice in the field of shape analysis to specify at least two different shape parameters, the first one being a global measure of the particle and the second, concentrating on

its morphological details (Imasogie and Wendt, 2004; Riebel et al., 1991). To assess morphological details of a globular structure, several parameters have been defined (Margarido and Robert 2003; Liu et al., 2003; Reisi and Niroumand, 2008; Paes et al., 2006; Browne et al., 2003; Mullin, 2001), each serving different purposes in relation to particular properties or features. During the processing of a material in the mushy temperature range, as a liquid, the material flows with relative ease and fills die cavities in a progressive fashion. The ease of flow is related to the morphology of the primary phase.

Of the several parameters that have been identified to assess morphological details, shape factor and sphericity are very prominent and stick out. For single particle, the size of which is defined by some length parameter or equivalent diameter, d , and density, ρ the following relationships can be applied:

$$\text{Volume} \quad v = f_y d^3 \quad (1)$$

$$\text{Mass} \quad m = f_y \rho d^3 \quad (2)$$

$$\text{Surface area} \quad s = f_s d^2 \quad (3)$$

The constants f_v and f_s may be called volume and surface shape factors, respectively [10]. For spherical (diameter = d) and cubic (length of side = d) particles:

$$f_y = \pi / 6 \text{ (Sphere) and } 1 \text{ (cube)} \quad (4)$$

$$f_s = \pi \text{ (Sphere) and } 6 \text{ (cube)} \quad (5)$$

The shape factors are readily calculated for other regular geometrical solids. The other prominent quantity that has been used to characterize phase morphology in microstructures is the sphericity, ψ , defined as the ratio of the surface area of a sphere having the same volume as the phase to the apparent estimated surface area of the phase (Mullin, 2001). This can be rewritten as:

$$\psi = \frac{(6f_y / \pi)^{2/3}}{f_s / \pi} \quad (6)$$

For isometric shapes ψ is close to 1 while for needles or platelets its value is much lower. Evaluation of ψ is useful for checking the values of f_v and f_s since $0 < \psi < 1$. Other quantities used to characterize shape include elongation ratio, flakiness (Mullin, 2001), roundness (Paes et al., 2006), etc.

OPERATIONAL CHARACTERISTICS OF A FURNACE

Heat flow patterns in furnaces have been studied using finite element (FE) analysis (Oluwole et al., 2009). This study revealed that the design of a furnace has effects on the heat flows characteristics of the furnace. The long term stability of the furnace is also dependent on the design. The thermal stability of the furnace determines the temperature profile within the furnace per time. Consider Figures 1 and 2, these show that the furnace design has significant effects on the temperature gradients in the furnace.

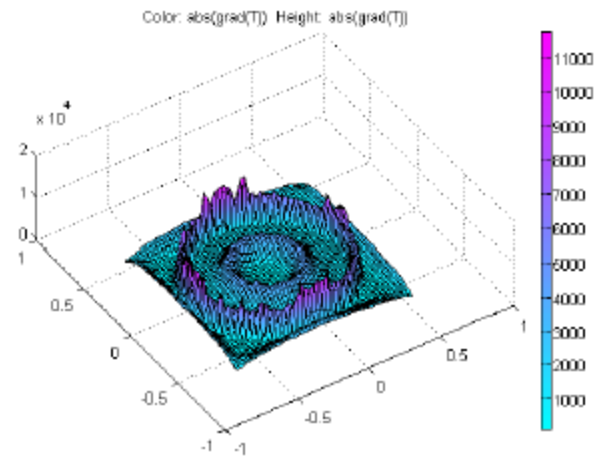


Figure 1: A 3-D Presentation of a Salt Bath Furnace showing Temperature Gradients during Heat Transfer in the Furnace (A high temperature gradient was observed in the air-gap insulation) (Oluwole et al., 2009).

MATHEMATICAL ANALYSIS OF 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):

$$T^* = T_m - G\Delta X = T_m - \Delta T_r \quad (7)$$

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).

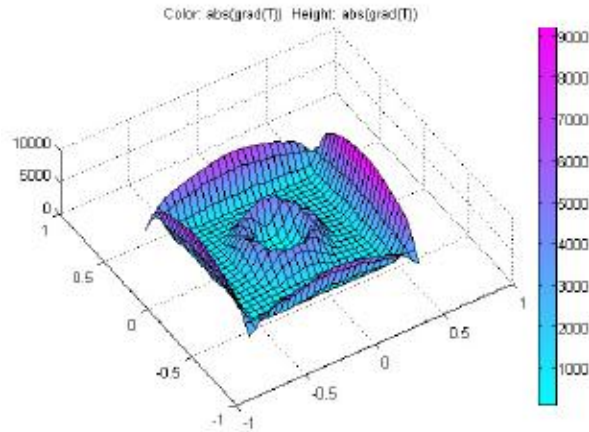


Figure 2: Salt Bath Furnace without Air-Gap Spacing Insulation within Refractory Lining showing Temperature Gradients During Heat Transfer in the Furnace (A high temperature gradient was observed concentrated in the glass wool fiber segment) (Oluwole et al., 2009).

But also,

$$\Delta G_L = S_L \Delta T_r \quad (8)$$

$$\Delta G_s = S_s \Delta T_r + 2V_s \sigma \lambda \quad (9)$$

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,

$$\Delta G_L = \Delta G_s \quad (10)$$

It follows that:

$$S_L \Delta T_r = S_s \Delta T_r + 2V_s \sigma \lambda \quad (11)$$

$$(S_L - S_s) \Delta T_r = 2V_s \sigma \lambda \quad (12)$$

$$S_s - S_L = -\Delta S \quad (13)$$

$$\Delta T_r = 2V_s \sigma \lambda / \Delta S \quad (14)$$

$$\Delta S = \Delta H / T_m \quad (15)$$

$$\Delta T_r = -2T_m V_s \sigma \lambda / \Delta H \quad (16)$$

But:

$$G\Delta X = \Delta T_r \quad (17)$$

$$G\Delta X = -2T_m V_s \sigma \lambda / \Delta H \quad (18)$$

$$1/\lambda = -2T_m V_s \sigma / G\Delta X \Delta H \quad (19)$$

But the curvature λ at a point is described as the limit (provided it exists) of the average curvature λ_{av} of an arc as the terminal point of the arc tends to its initial point (Bermant and Aramanovich, 1989). For arc M_0M_1 , as the terminal point of the arc M_1 tends to its initial point M_0 .

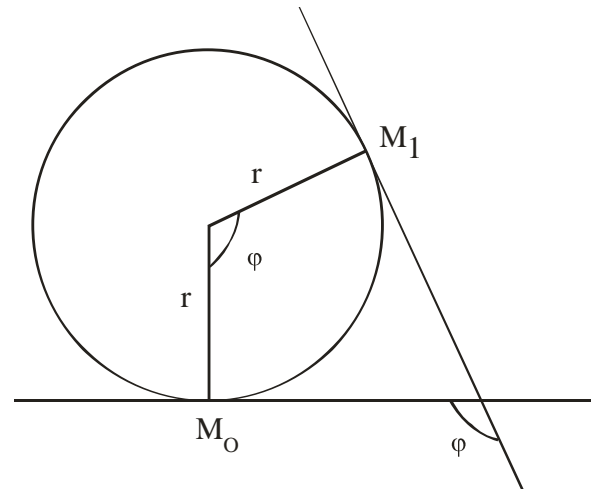


Figure 3: Geometric Description of Relationship between r , ϕ , and Curvature (λ).

$$\lambda = \lim_{M_1 \rightarrow M_0} \lambda_{av} = \lim_{M_1 \rightarrow M_0} (\phi / M_0M_1) \quad (20)$$

Where ϕ is the angle of contingence of the arc (in radians), so;

$$M_0M_1 = r \phi \quad (21)$$

Thus;

$$\lim_{M_1 \rightarrow M_0} (\varphi / M^0 M^1) = \varphi / r\varphi = 1/r \quad (22)$$

$$\text{Therefore: } \lambda = 1/r \quad (23)$$

$$\text{Then: } r = -2T_m V_s \sigma / G \Delta X \Delta H \quad (24)$$

The thermal gradient G is dependent on the stability of the furnace (Oluwole et al., 2009). If the temperature field of the system is transient i.e.;

$$T = f(x, y, z, t); f'_t \neq 0 \quad (25)$$

Where x, y, z are point coordinates, t is time. The thermal gradient G will be dependent on time and the value of r will vary with time. Transient temperature fields are experienced during heating and cooling of a system.

During isothermal heating, the temperature field is steady i.e.,

$$T = f(x, y, z); f'_t = 0 \quad (26)$$

G will be essentially constant and independent of time. This gives an essentially constant value for r . This results in a spherical morphology. This shows that the ability of the heat treatment furnace to maintain an efficient steady-state will affect the morphology of the alloy. Also, value of G (whether $G < 0$ or $G > 0$) will affect the concavity or convexity of the morphology of the resulting microstructure.

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