Journal of Alloys and Compounds 686 (2016) 727–732

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Modeling of yield strength in binary hypoeutectic alloy under high pressure solidification

Chunming Zou [a, **], Wei Jiang [a, b, *], Hongwei Wang [a], Zhonglue Hu [c], Zunjie Wei [a, ***]

[a] National Key Laboratory of Metal Precision Hot Forming, Harbin Institute of Technology, Harbin, 150001, China
[b] Department of Physics, Pennsylvania State University, University Park, PA, 16802, United States
[c] Department of Mechanical Engineering, Texas Tech University, Lubbock, TX, 79409, United States

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form
6 June 2016
Accepted 8 June 2016
Available online 11 June 2016

Keywords:
High-pressure
Mechanical properties
Metals and alloys

ABSTRACT

A new mathematical model was developed to predict the yield strength under high pressure solidification. This model can be used in the binary hypoeutectic alloy system which contains solid solution and intermetallic compound. Following this model, the total change of yield strength under high pressure is affected by solid solution, eutectic spacing and grain size. This effect can be quantitatively measured by the change of a pressure-solid solubility function $f(P)$. This model reveals that along with the variation of $f(P)$, change in the solubility and eutectic spacing lead to opposite influences on yield stress. Application of the model to the binary Mg-20.3 wt%Al solidified under different pressure was conducted. It was found that this model can perfectly explain the change in the yield strength of Mg-20.3 wt%Al alloy solidified under high pressure. This model can provide theoretical guidelines for choosing reasonable solidification pressure to optimize microstructure and properties of binary hypoeutectic alloy in high pressure solidification.

1. Introduction

Alloys of hypoeutectic composition are extensively used for different engineering applications because they have relatively low melting points, excellent fluidity, and good mechanical properties [1,2]. These excellent properties are highly dependent on the fraction and morphology of eutectics in the hypoeutectic alloy. So the eutectic is keeping to be a hotspot of research, more and more attention is paid to different aspects of eutectic these years, such as dynamic effects, stability of growth, simulation and mathematical prediction, especially the prediction and control of the mechanical properties is meaningful to the application [3–5].

The fraction and morphology of the eutectic in hypoeutectic alloy can be effectively controlled by pressure under high pressure solidification [6]. The ever increasing chamber dimension and pressure in the high-pressure manufacturing equipment allows high-pressure manufacturing has become a critical solution for preparing materials with superb properties nowadays [7–9]. In previous studies, Wang [10], Jie [11], Teng [12] and Obiekea KN [13] has been suggested that mechanical properties such as yield stress (YS), tensile strength and hardness will be effected by high pressure. But all of these works cannot give conclusions which agree well with the experimental results and the relationship between mechanical properties and pressure has not been sufficiently discussed, especially almost no existing mathematical model of the mechanical properties under high pressure. Our previous studies [6] have developed a model that effectively reveals the relationship between the solidification pressure and the eutectic spacing, which makes it possible to identify the quantitative relationship between solidification pressure and mechanical properties. It would be quite beneficial for research and applications purposes to establish an accurate mathematical model that describes the relationship between pressure and mechanical properties. More specifically, it can be used to predict the influence of pressure on the mechanical properties of alloy, and thus facilitates the identification of an optimized pressure under which yields best mechanical properties.

In this article, a new mathematical model was developed to represent the yield strength of the binary hypoeutectic alloy solidified under high pressure. The binary hypoeutectic alloy contains

* Corresponding author. National Key Laboratory of Metal Precision Hot Forming, Harbin Institute of Technology, Harbin, 150001, China.
** Corresponding author.
*** Corresponding author.
E-mail addresses: zouchunming1977@163.com (C. Zou), zdjiangwei@hotmail.com (W. Jiang), weizj@hit.edu.cn (Z. Wei).

http://dx.doi.org/10.1016/j.jallcom.2016.06.067
0925-8388/

the first structural phase (solid solution) and the second structure (eutectic which consist of solid solution and intermetallic compound). The Mg-20.3 wt%Al solidified under different pressure were investigated to prove the correctness of the model. This work can provide theoretical guidelines for choosing reasonable solidification pressure to optimize microstructure and properties of binary hypoeutectic alloy in high pressure solidification.

2. Mathematical model

The focus of the present work is to model the change of the yield strength under high pressure. Yield strength is a reflection of the amounts of the two phases and their respective mechanical properties, a hard phase and a soft phase together will to some extent average out to an in-between value. For hypoeutectic (solid solution matrix and eutectic), the yield strength is decided by both the solid solution and eutectic. The following basic equation is usually used to analyzed the yield strength of materials with mixed structural constituents [14,15].

$$\sigma_y = f_\alpha^n \sigma_\alpha + (1 - f_\alpha^n)\sigma_e \tag{1}$$

where σ_y is the yield strength of the alloy, σ_α is the yield strength of the first structural phase (primary solid solution in hypoeutectic alloy), σ_e is the yield strength of the second structural phase (eutectic in hypoeutectic alloy), f_α is the volume fraction of solid solution and $(1-f_\alpha)$ is the volume fraction of eutectic. Thus the yield strength of the aggregate is presented as the sum of the separate contributions from solid solution and eutectic and weighted according to their volume fractions.

Several investigators have reported the solid solution strengthening in alloys [16–18] and make considerable work in the quantification of the relationship between solid solubility and yield strength. According to the work of Akhtar and Teghtsoonian [19], the yield strength of solid solution can be expressed by a function of solid solubility. It takes account of the solid solution strengthening effect and Hall-Patch relationship. The yield strength of solid solution matrix can be expressed as Eqn. (2).

$$\sigma_\alpha = \sigma_0 + k_\alpha c^n + k_d d^{-1/2} \tag{2}$$

where σ_α and σ_0 is the yield stress of solid solution and pure metal respectively; k_α and k_d is parameters determined for the material, for convenience, an average $k_d = 0.3\ \mathrm{MPam}^{-1/2}$ will be taken for the analysis (Mg alloy) [20]; c is the atom concentration; $n = 1/2–1$. It has been reported that the value of n is similar to 1 at high concentrations of solute atoms, while it is similar to 0.5 at low concentrations [21].

$$k_\alpha = mB \tag{3}$$

B is the solid solution hardening rate on the basal plane and m is the Taylor orientation factor connecting the tensile flow stress of the polycrystal to the resolved shear stress of the relevant slip systems. Akhtar and Teghtsoonian [19] determined B as 21.2 and 39.5 for $n = 1/2$ and 2/3, respectively, but no theoretical or experimental value has been reported for m in Mg alloys, although Lukac [22] suggested that it should lie between 4 and 6. Due to lack of relevant data, a mean value of $m = 5.5$ adopted in this paper.

According to the work by M. Zhao et al. [23], for normal crystalline materials with $d > 10\ \mu m$, the change of $d^{-1/2}$ term is negligible. When $10\ \mu m > d > 100$ nm, the model prediction is in reasonable agreement with experimental results.

Previous studies [24–26] showed the solid solubility changed apparently under high pressure. And according to the contribution given by L. Kaufman and Y. Minamino [27], who set up a mathematical model for solid solubility under high pressure, obtaining:

$$X^\alpha(P) = X^\alpha(0) + \frac{PdX^\alpha}{dP} \tag{4}$$

$$\frac{\partial X^\alpha}{\partial P} = \frac{X^\alpha\left(\frac{V^B - V^\alpha}{X^B - X^\alpha} - \frac{\partial V^\alpha}{\partial X^\alpha}\right)}{RT} \tag{5}$$

where superscripts α and B indicate the solid solution and second phase. The term X(P) is the mole fraction of solid solubility at pressure P, X^α is equal to C_s; V is the molar volume; R is the gas constant; and T is the temperature.

The X can be defined as a function of pressure, a function present the relationship between solid solubility and pressure.

$$\mathrm{X} = \mathrm{f(P)} \tag{6}$$

So the c, solid solubility can be defined as a function of pressure. This function can provide the corresponding values of solid solubility $f(P)$ for the selected pressure if the volumetric conditions of the phases in binary alloy are known. And the Eqn. (2) can be expressed as

$$\sigma_\alpha = \sigma_0 + k_\alpha f(P)^n + k_d d^{-1/2} \tag{7}$$

Modi.O.P, etc. [28], Dollar M [29] and Gladshtein [30] have established formulas about the effect of interlamellar spacing on mechanical properties based on the study on fully pearlite. The yield strength of the eutectic can be simply expressed as functions of the inverse of the square root of the interlamellar spacing ($\lambda^{-1/2}$). The distance between two consecutive lamellae of one phase in one eutectic cluster is termed as eutectic spacing. In the irregular eutectic, the spacing between lamellae varies and is non-uniform. Hence, for irregular eutectic, eutectic spacing is often referred as the average spacing.

$$\sigma_e = \sigma_{00} + K\lambda^{-1/2} \tag{8}$$

where σ_e is the yield strength of eutectic, σ_{00} is the internal frictional strength of ferrite with infinite mean free path and K is the dislocation locking constant.

The pearlite is eutectic which is composed of ferrite and cementite. Ferrite, also known as α-Fe is solid solution which is ductile, and the cementite is a compound which is hard, brittle. This composition is very similar to some binary alloy eutectic which composed to ductile solid solution and hard, brittle intermetallic compound, such as the Mg-Al alloy which is composed to α-Mg, a ductile solid solution and γ-$Mg_{17}Al_{12}$, a hard, brittle compound. So we can quote the Eqn. (8) to the Mg-Al system or other similar systems.

According to our study [6] the morphology of eutectic in hypoeutectic alloys changed remarkably under high pressure solidification. And a mathematical model [6] has been developed for the relationship between eutectic spacing and pressure:

$$\lambda = \varphi^2 \theta \frac{f(P)}{2\pi(C_l - f(P))} \tag{9}$$

where f(P) is same as mentioned earlier, φ and θ are constant for a given system, C_l is the composition of the liquid alloy.

By inserting Eqn. (9) into Eqn. (8), the Eqn. (8) is obtained as: