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Dependence of microstructure on the cooling rate for a modified austenite medium Mn steel

GAO-FEI LIANG, ZHEN-MING XU, JIAN-GUO LI
School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200030, People's Republic of China
E-mail: Zmxu@sjtu.edu.cn

An austenite medium Mn steel reinforced with well distributed γ-(Fe, Mn)$_3$C granular eutectics (abbreviated EAMC) has been prepared by modifying with Si-containing combined agent [1]. The experiment observations and theoretical analysis indicate that the pseudo-eutectics (non-eutectic composition) are formed in the liquid pockets among the primary austenite dendrites at the later stage of solidification. The previous investigation indicates that the cooling rate has notable effect on the microstructure of EAMC, as well as the scales of eutectics such as the volume fraction (f) and diameter (d), and the appearance of others phases such as the pearlite and carbides. In the directional solidification experiments, one may study precisely the nucleation time and position of each phase and the dependence of microstructure on growth rate (cooling rate). Therefore, directional solidification of EAMC has been carried out using Vertical Bridgman method. The microstructure scales of the eutectics as a function of growth rate (V) is described and discussed in the present work.

The EAMC master samples modified with the controlled α_k were prepared by melting weighed quantities of pig iron, steel scraps, Fe-Mn alloy (Fe-80%Mn-1.0%Si-1.2%C), and Ca-Si agent (Fe-28%Ca-65%Si-2.4%Al-0.8%C). After allowing time for melt homogenization, molten alloy was poured into the prepared bar molds (100 mm in length 7 mm ID and 8.5 mm OD). The chemical composition of the bars is presented (wt%) as follows: 1.25C, 1.06Si, 6.60Mn, 1.06Al, 0.10Ca, 0.02S, 0.02P, and balance Fe. Directional solidification was performed using a high temperature gradient Bridgman-type unit in the protective argon atmosphere. Detailed descriptions of the unit were given elsewhere [2]. Specimens were directionally solidified at different growth rate (2.18–500 μms^{-1}) with a constant temperature gradient about 800 Kcm^{-1}. They were pulled rapidly into Ga-In reservoir after 30 mm steady growth. Samples were ground, polished, and then etched in a solution of 4 ml HNO_3 and 96 ml C_2H_5OH. A video-image digital analysis system (VIDAS) and Vickers durometer (VD) were used in the work. VD analyses indicate that the microhardness of eutectic (Hv 560–800) is less than that of carbide (Hv 1200–1400). VIDAS observations show that the color of eutectic is white, but that of carbide is black in the optical. Thus, the eutectic and carbide can be differentiated by color and/or microhardness. The volume fraction of eutectics (f) can be gained directly by using VIDAS. The diameter (d) of eutectic is

$$d = l/\pi \tag{1}$$

where l is the perimeter of eutectic (μm).

The photographs of the specimens on V and microstructural parameters for directionally solidified EAMC are given in Fig. 1. It can be seen that there are four critical growth rates (μm/s), 6.9, 13.33, 20.95, and 450. If the growth rate $V < 6.9$ μm/s, the microstructure of EAMC is composed of pearlite (Hv 260–450, tested with VD), granular (Fe,Mn)$_3$C carbides in grain, network carbides surrounding grain, and retained austenite. If $13.33 < V < 20.95$ μm/s, the granular γ-(Fe,Mn)$_3$C eutectics and granular/needle-like (Fe,Mn)$_3$C carbides are unevenly distributed in the grain surrounded by the inter-boundary carbides. If $20.95 < V < 50.6$ μm/s, the microstructure is similar to that at $13.33 < V < 20.95$ μm/s, but without the needle-like carbides in grain. If $50.6 < V < 450$ μm/s, Lots of granular eutectics are well distributed in the austenite matrix surrounded with network carbides. If $V > 450$ μm/s, the microstructure likes that at $50.6 < V < 450$ μm/s although the inter-boundary (Fe, Mn)$_3$C carbides are absent. A shorthand nomenclature for microstructural descriptions is as follows: A = austenite, P = pearlite, E = eutectic, C_1 = network carbide, C_2 = granular carbide in the matrix, and C_3 = needle-like carbide. The dependence of microstructure on the growth rate is given schematically in Fig. 2.

Fig. 3 shows the growth interface morphology for the EAMC at 6.9 μm/s. Some carbides may form on subsequent cooling to the eutectoid temperature if V is low. C and Mn partitioning occurs primarily in the boundary (marked by a single solid arrow), following the regions richer in C, Mn in the grain (marked by a single dot arrow). Below the eutectoid temperature, the austenite may be unstable and transform to pearlite on cooling, meanwhile some needle-like carbides may partition out of the grain at temperature ranging from 200–300 °C if the C and Mn contents in the retained austenite are sufficiently high [3]. If V is sufficiently high, carbides and pearlites may not form because the diffusion coefficients of C and Mn decrease with increasing V.

Fig. 4 shows the variation in f with V for EAMC. It can also be seen from Fig. 4 that f initially increasing with V attains a peak and then follows a decreasing

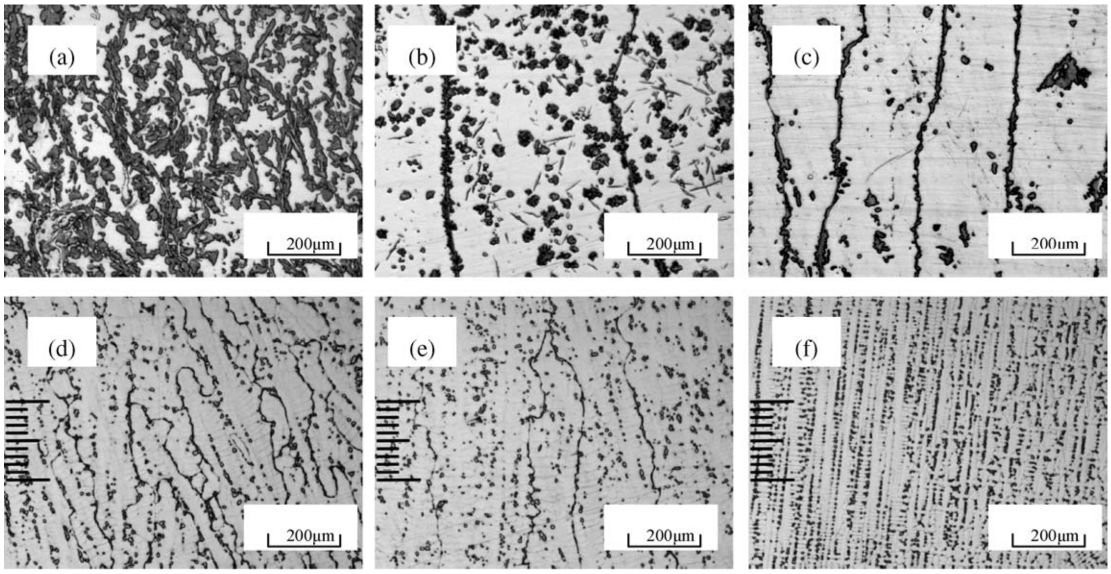

Figure 1 Microstructure of longitudinal sections at different growth rates. (Bottom-up growth for EAMC): (a) 6.9 μm/s, (b) 13.33 μm/s, (c) 20.95 μm/s, (d) 50.6 μm/s, (e) 180 μm/s, and (f) 450 μm/s.

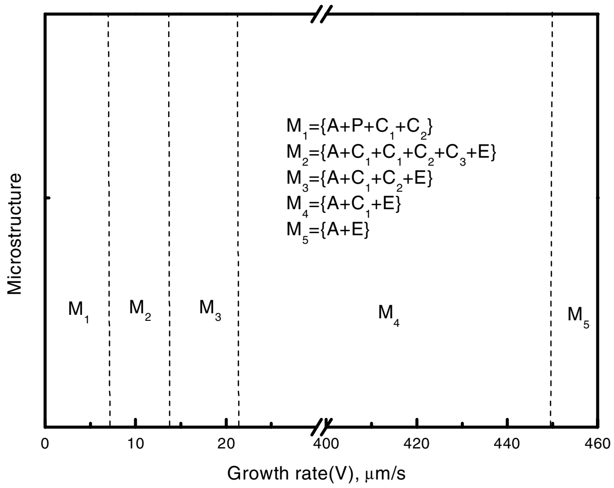

Figure 2 Dependence of microstructure on the growth rate: A = austenite, P = pearlite, E = eutectic, C_1 = network carbide, C_2 = granular carbide in the matrix, and C_3 = needle-like carbide.

trend. The crystal growth depends largely on the nucleation rate (N) and the liquid diffusion coefficient (D_L) of solute. N increases, but D_L decreases with increasing super-cooling. N plays the key role when V is relatively small, which leads to the refinement of primary austenite dendrites. The higher V, the larger the super-cooling degree of the liquid pockets among the primary austenite dendrites at the later stage of solidification. Therefore, the mushy zone depth and the amount of liquid pockets increase with increasing V. Also, there is a coupled-zone for γ-$(Fe,Mn)_3C$ eutectic in the Fe-C-Mn system, as shown schematically in Fig. 5. As a characteristic of non-equilibrium solidification, the γ-$(Fe,Mn)_3C$ coupled-zone is enlarged as increasing super-cooling attributed to the higher V, resulting in the greater probability that in a given time the eutectics will grow and initiate solidification. Therefore, f increases initially with V. Otherwise, lower D_L restricts the eutectic growth when V is sufficiently high, consequently, f decreases with V.

Fig. 6 shows the effect of V on d of the eutectics. It is found that d decreases with V. The nucleation rate (I_c), as a function of the undercooling (ΔT) is [4],

$$I_c = B_1' \exp\left[-\frac{16\pi\sigma^3 T_M^2 V_s^2}{3\Delta H^2 \Delta T^2 kT} f(\theta)\right] \tag{2}$$

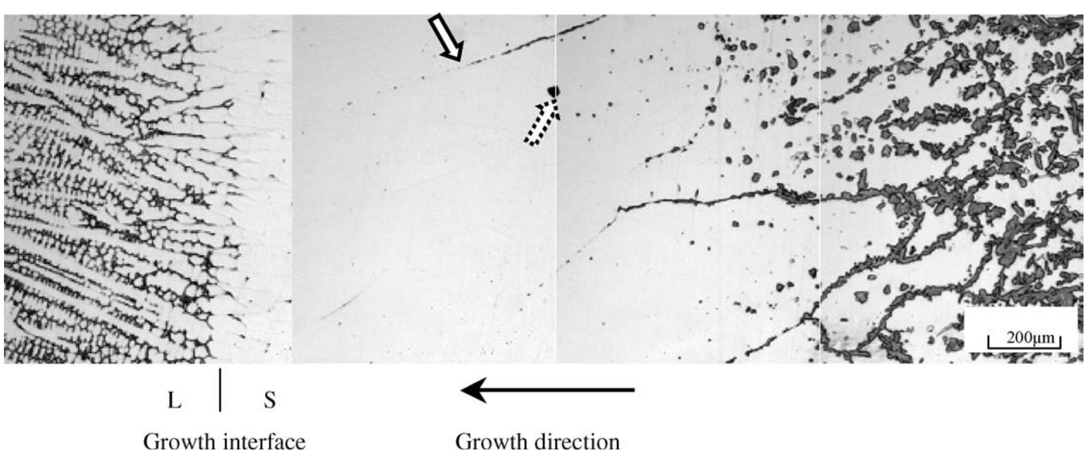

Figure 3 The solid/liquid (S/L) interface morphology for EAMC at 6.9 μm/s.

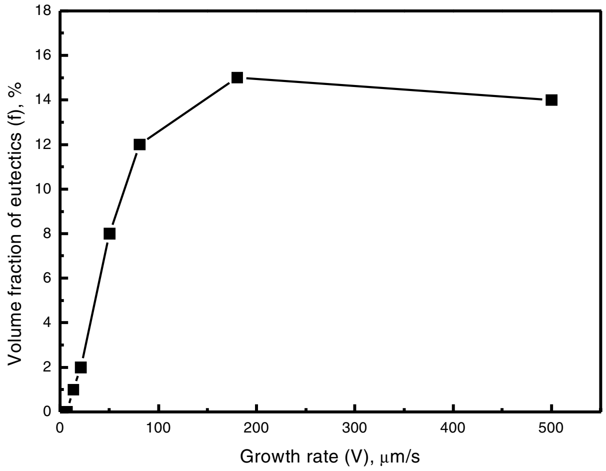

Figure 4 Variation of volume fraction of granular eutectics particles with growth rate.

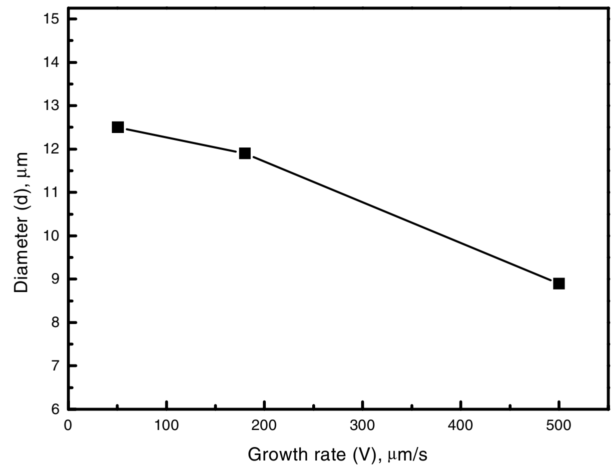

Figure 6 Variation of diameter of granular eutectics particles with growth rate.

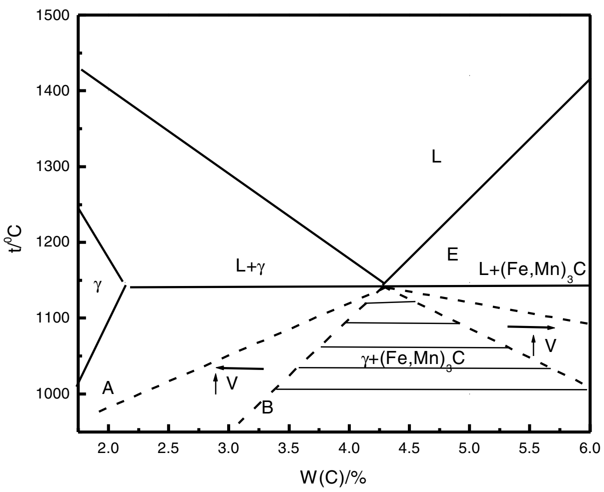

Figure 5 Effect of growth rate (V) on the γ-(Fe,Mn)$_3$C coupled-zone (shadow region). The zone is enlarged as V increases.

where B_1' is a constant depending on critical nucleus size, surface energy, and the number of surface atoms on the substrate per unit volume of liquid, σ surface energy, T_M melting point, V_s volume for the solid phase, ΔH enthalpy, k Boltzman's constant, T temperature, and θ contact angle. As discussed above, the larger V, the higher ΔT of the steel liquid on solidification. It can be concluded from Equation 2 that the nucleation rate of the primary austenite increases with increasing V. Furthermore, the thickening time of the primary austenite decreases as V increases. Therefore, the primary austenite dendrites are refined with increasing V. The liquid pockets among the primary austenite dendrites limit the growth of eutectics. As a result, d decreases with the refinement of primary austenite dendrites attributing to the higher V.

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