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Coarsening Behavior of Faceted Grains in a Liquid Matrix: Model Calculation and Experimental Observations

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In many solid-liquid two-phase systems, the shape of grains is faceted, either fully or partially. Typical systems include liquid phase-sintered carbides (WC, SiC, NbC, ···), nitrides (Si_3N_4, SiAlON, AlN, ···) and oxides (Al_2O_3, $BaTiO_3$, $MgAl_2O_4$, ···). In these systems, the grain coarsening behavior does not appear to follow the classical Lifshiftz-Slyozov-Wagner (LSW) theory of Ostwald ripening. A number of experimental observations have suggested and confirmed that abnormal grain coarsening occurs in systems with faceted grains [1-3]. This presentation summarizes our experimental results as well as theoretical calculations on grain coarsening behavior in faceted systems.

Grain coarsening in a liquid matrix is a result of growth and dissolution of single crystal grains. According to crystal growth theories, the growth rate of a crystal with a spherical shape is governed by diffusion of atoms in the liquid matrix and is linearly proportional to the driving force, as schematically shown by a dashed straight line in Fig. 1(a). The growth rate of a faceted crystal is, on the other hand, governed either by diffusion or interface reaction above or below a critical driving force Δg_c, respectively, as shown by a solid line in Fig. 1(a) [4-6]. The non-linear region governed by interface reaction is expressed as an exponential function of the driving force for 2-dimensional nucleation and growth or a square function for screw dislocation-assisted growth.

For a system with numerous grains, each grain has its own driving force for growth or dissolution. The maximum driving force for growth, Δg_{max}, is for the largest grain and the maximum driving force for dissolution for the smallest grain, with the latter being close to $-\infty$. The contribution of the nonlinear region to the overall coarsening behavior can be characterized by the relative values of Δg_{max} and Δg_c [3,7]. Figure 2 schematically depicts typical cases of varying Δg_c (for a fixed Δg_{max} at the beginning), that can result in (a) normal, (b) pseudo-normal, (c) abnormal and (d) stagnant coarsening behavior [3,7]. Fig. 2(e) gives the variation of average grain radius with calculation time steps for cases (a) – (d) [8]. Even for a fixed Δg_c, however, the type of coarsening behavior can change with annealing time because Δg_{max} decreases with grain coarsening [7,9]. Different types of coarsening behavior can also appear in systems with varying Δg_{max} under a constant Δg_c [3,7].

Numerous experimental observations support the above prediction and calculations of grain coarsening behavior [1-3,9,10]. The principles of coarsening behavior based on the concept of the coupling effects of Δg_{max} and Δg_c have also been found to be applicable to the prediction and interpretation of grain growth behavior in single phase systems with faceted boundaries [11,12].

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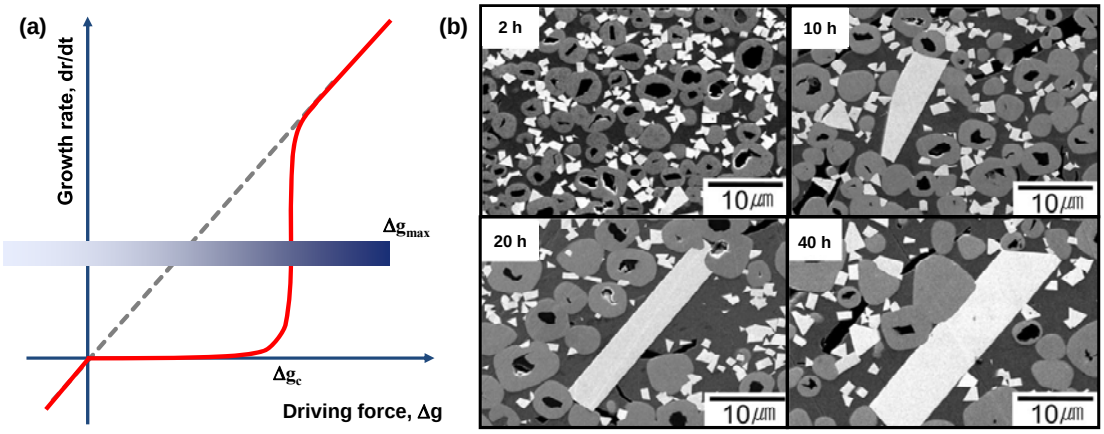

Fig. 1. (a) Schematic of growth rate vs. driving force for a spherical (dashed line) and a faceted grain (solid line). (b) Microstructures showing normal growth of spherical Ti(W)C grains (grey, often with a black spot of a TiC core) and abnormal growth of faceted WC grains (white) in the same Co liquid matrix (dark) during sintering of TiC-WC-Co at 1450°C [10].

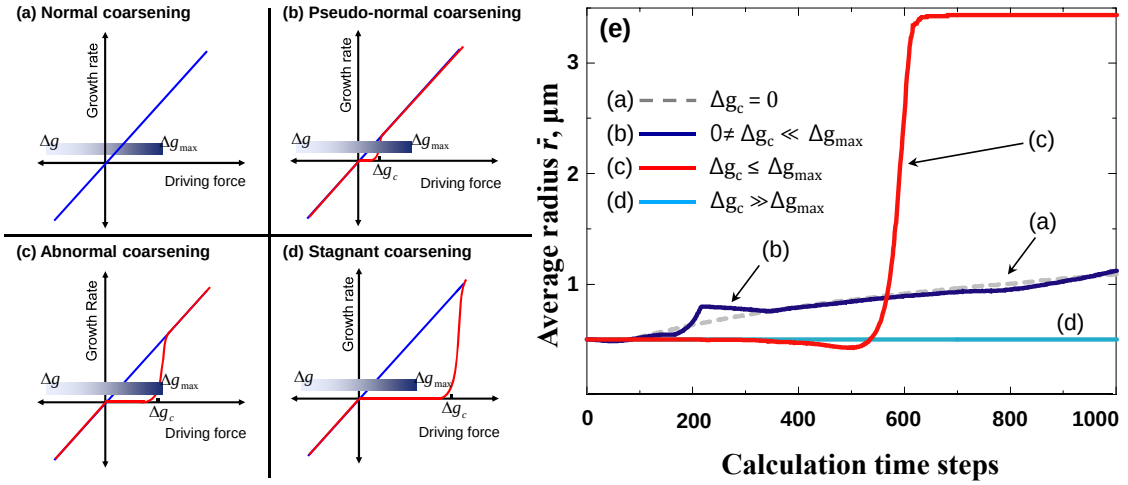

Fig. 2. Schematics showing the coupling effect of Δg_c and Δg_{max} on grain coarsening: (a) normal coarsening for $\Delta g_c = 0$, (b) pseudo-normal coarsening for $0 \neq \Delta g_c \ll \Delta g_{max}$, (c) abnormal coarsening for $\Delta g_c \leq \Delta g_{max}$ and (d) stagnant coarsening for $\Delta g_c \gg \Delta g_{max}$. (e) Calculated changes in average grain radius with calculation time steps for cases (a) – (d) with initial average particle radius of 0.5 μm and standard deviation of 0.05 μm [8].