
PRINCIPLES OF THE AUSTENITIZATION — OF STEELS —

Charlie R. Brooks

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CHARLIE R. BROOKS

*Materials Science and Engineering Department,
The University of Tennessee,
Knoxville, Tennessee 37996, USA*



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Preface

The heat treatment of steels in the austenite region, whether for homogenization or for subsequent hardening, is a crucial step in the processing of steels. Understanding the purposes of austenitizing is important for those involved in the heat treatment of steels, designing steel components and specifying steels. This book introduces the principles of the response of steels to the austenitizing process. Familiarity with the general ideas of the heat treatment of steels is useful for use of this book, but an introductory materials or metallurgy course would be sufficient background. The level of treatment has purposefully been kept introductory, with the theoretical aspects which are involved only outlined, frequently using simplified models. Appropriate references are cited to point the reader to more detailed, realistic and current models for the associated processes, e.g. grain growth. Thus, this book should serve as a useful reference for metallurgists, materials scientists and engineers, and other engineers who require a review of this topic.

In the appendices are tables containing metric conversion factors, temperature scale conversions, and hardness scale conversions for steels, and other useful information. There is also a detailed glossary of terms.

I would like to thank the many researchers and organizations for allowing me to use information from their work; the exact citations are given in the text of the book. I especially appreciate ASM International for their permission to make many citations from their publications, and Dr Len Samuels for allowing me to utilize micrographs from his book *Optical Microscopy of Carbon Steels* (American Society for Metals, Metals Park, OH, USA, 1980). I also thank my wife, Sue, for editing assistance.

Charlie R. Brooks

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1 Introduction

Steels are heat treated in the austenite region for two main purposes. One is to chemically homogenize the cast ingot, and the other is to obtain austenite suitable for subsequent cooling for hardening. In most wrought steel products which are formed from the ingot state, the steel undergoes many hot deformation operations in the austenite range, and in the process undergoes further chemical homogenization. Thus, when a wrought steel part is ready for final heat treatment, austenitizing can be done at a considerably lower temperature than was required for homogenization. The primary concern in austenitizing for heat treatment is to maintain a uniform austenite grain size without coarsening and to attain a uniform structure.

The two types of austenitizing treatments are for different reasons, and they will be discussed in separate chapters. First, though, a brief review of crystallization is given. Then, since the homogenization process is carried out to remove chemical segregation associated with the cast ingot, a brief review of the origin of this segregation is presented, and then the cast ingot structure of steels and the homogenization treatment of ingots are examined. In the austenitizing of steel for the purpose of subsequent hardening, control of the austenite grain size is very important, and therefore a review of the concepts of grain growth is presented before examining this austenitizing treatment.

2 The Process of Crystallization and Chemical Segregation

This chapter reviews briefly the process of crystallization in metals and alloys in order to make clear the origin of chemical segregation in steels. More detail about solidification of alloys can be obtained from Refs 1–4.

2.1 THE FORMATION OF A CRYSTAL FROM A LIQUID

The general principles involved in the formation of a crystal from a liquid are now outlined. More detail about nucleation and growth are given in Appendices 1 and 2.

When a liquid of a pure material (e.g. Cu, Fe, NaCl) is cooled below the melting temperature, the energy of the material is lowered if it can convert to its equilibrium crystalline form. This is accomplished by the formation of microscopically small crystalline regions, called *nuclei*, and their growth. There is a decrease in the energy of the system due to the formation of the more thermodynamically stable crystal, but there is a concomitant increase in energy due to the formation of the liquid–solid interface. The decrease in energy occurs because the energy of the crystalline form is less than that of the liquid. This energy contribution is proportional to the volume, e.g. $\frac{4}{3}\pi r^3$ if the crystal is a sphere. The positive contribution to the energy change occurs because the surface energy is positive. It is proportional to the surface area, e.g. $6\pi r^2$ if a sphere. Upon growth of the crystal the energy of the system first increases. However, when a critical size is attained, further growth is accompanied by a decrease in energy of the system, and thus the crystal will continue to grow. This process of nucleation and growth is illustrated schematically in Fig. 2.1.⁴

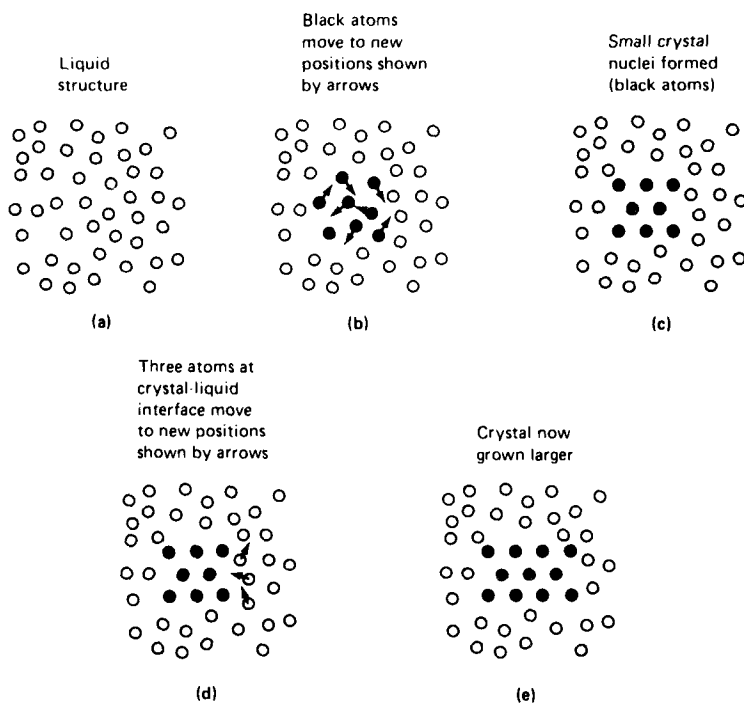


Fig. 2.1. Schematic illustration depicting homogeneous nucleation of a crystal and its growth in a liquid. (From Ref. 4, reproduced by permission of American Society for Metals.)

The rate of crystallization depends upon both the *nucleation rate* and the *growth rate*. Since both processes involve the movement of atoms, their rates depend upon the atom mobility, which is proportional to $\exp(-Q/RT)$, where Q is the *activation energy* for the movement of the atom, R is the ideal gas constant and T the absolute temperature. Note that this expression implies that the rate of crystallization will be zero at absolute zero, and a maximum just below the melting point. However, for small undercooling, the thermodynamic driving force is small, and hence the rate of crystallization is low. As the temperature decreases, this driving force increases (becomes more negative) and the rate of nucleation and of growth increases. Eventually this is overcome by the decreasing atom mobility. Thus, the nucleation and growth rate are a maximum at an intermediate temperature (although not the same temperature for

both), and hence the rate of crystallization is a maximum at an intermediate temperature. This dependence is illustrated in Fig. 2.2.

Note that if the liquid can be cooled to a sufficiently low temperature, below the maximum in the curve in Fig. 2.2(b), without crystallization beginning, then the temperature may be so low that the rate of crystallization is too low for freezing to occur except for very long times, e.g. years. Thus, a metastable liquid would be obtained. However, in commercial alloys cast into molds and in which heterogeneous nucleation occurs, the rate of increase of the nucleation rate with temperature below the freezing temperature is such that even very rapid cooling, e.g. 1000°C/s is not sufficient to prevent nucleation.

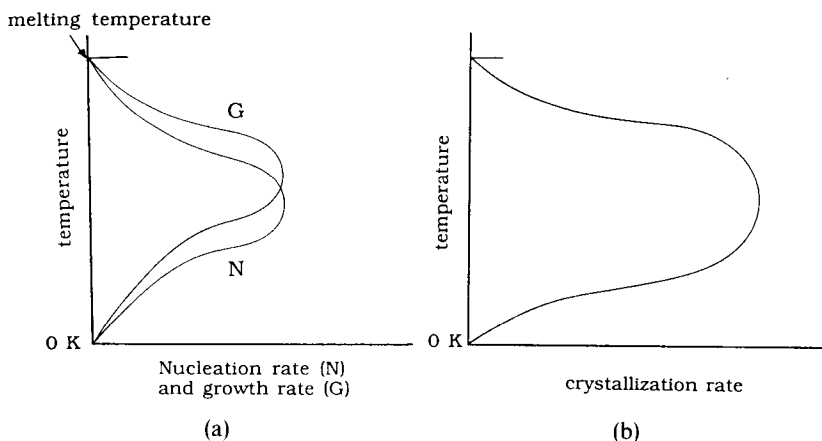


Fig. 2.2. Schematic illustration of the temperature dependence of the nucleation rate, N , and the growth rate, G , during solidification. Also shown is the crystallization rate, which depends on both N and G .

2.2 AS-CAST GRAIN SHAPE AND SIZE

The rate at which atoms attach to the crystal surface is greatest in certain crystallographic directions. This leads to the crystal taking on a geometric shape (Fig. 2.3(a)).⁵ In many cases, the crystal will develop side arms, as depicted in Fig. 2.3(b),⁶ and a crystal with this geometry is called a *dendrite*.

Of special importance is the grain (crystal) size after freezing, which

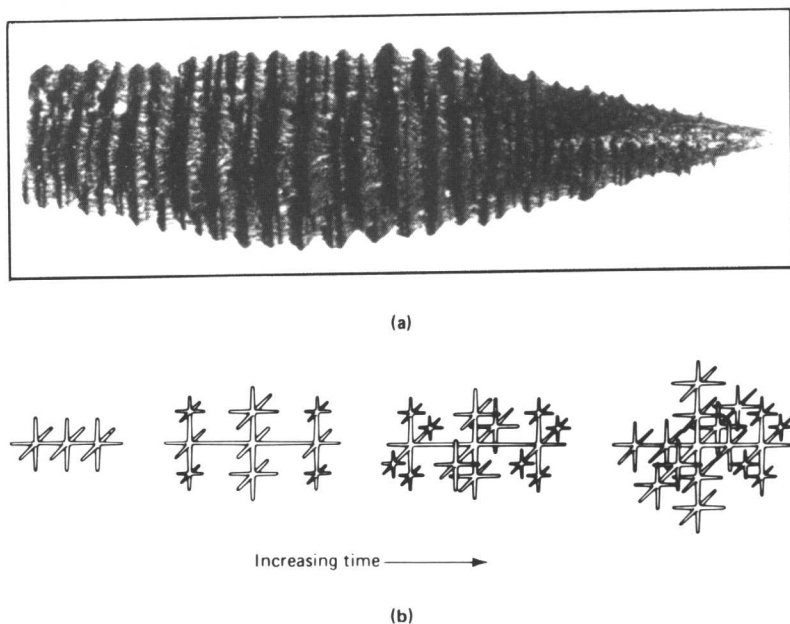


Fig. 2.3. (a) Photograph of a large, 9 in long dendrite which formed in a steel. (From Ref. 5.) (b) Schematic illustration of the growth of a dendritic crystal. (Adapted from Ref. 6.)

depends upon the nucleation rate and growth rate. If the nucleation rate is very high, and the growth rate low, then the many nuclei quickly impinge upon other growing grains, and a small final grain size is attained. If the nucleation rate is low, and the growth rate high, then few nuclei can form before crystallization is complete, giving a large grain size. Thus, the ratio of the growth rate, G , and the nucleation rate, N , controls the final grain size. This is illustrated in Fig. 2.4.⁴

The formation of crystals shown in Fig. 2.1 is for *homogeneous* nucleation. However, in commercial materials, there already exist numerous crystalline surfaces which act as favorable sites upon which nucleation will occur. Such nucleation is called *heterogeneous* nucleation. For example, the walls of the mold into which the liquid is poured are colder than the liquid and consist of crystals of the mold material. Thus, the surface of these crystals is a common location for crystals to nucleate

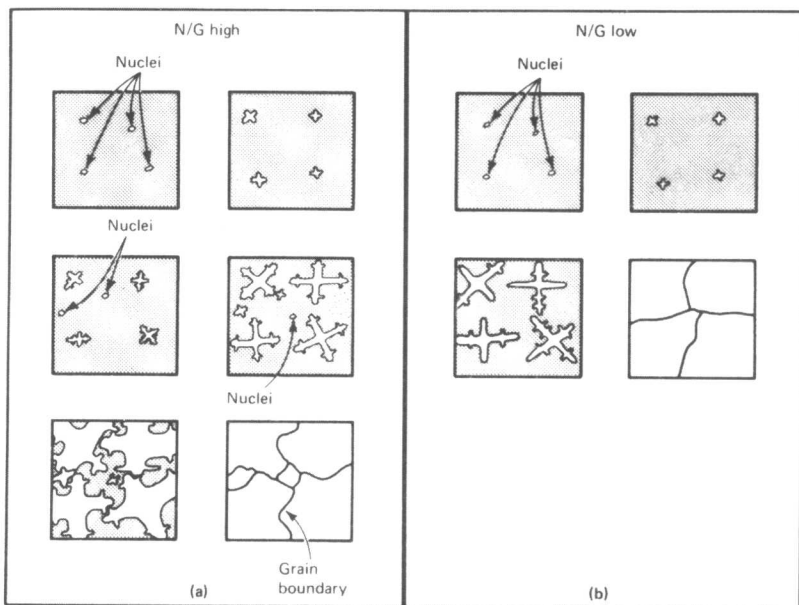


Fig. 2.4. Schematic depiction of the effect of the ratio of the nucleation rate, N , to the growth rate, G , on the final grain size. The higher N/G ratios give a smaller (finer) grain size. (From Ref. 4, reproduced by permission of American Society for Metals.)

from the liquid. Crystals generally will grow faster the greater the temperature gradient, and thus a crystal which forms on a cold mold wall will tend to develop an elongated shape. Also, since growth is fastest along certain crystallographic directions, crystals nucleated on the mold wall and with one of these directions approximately perpendicular to the wall will be favored to develop into elongated crystals. The formation of these *columnar* grains is depicted in Fig. 2.5.⁴ An example of such grain structures in castings is shown in Fig. 2.6.⁷

To enhance the formation of an *equiaxed* and fine grain structure, the liquid can be inoculated with fine crystalline particles of high-melting-point materials to act as heterogeneous crystallization nuclei upon casting the material. The effect of adding such a grain refiner on the grain structure of aluminum is shown in Fig. 2.7.⁷

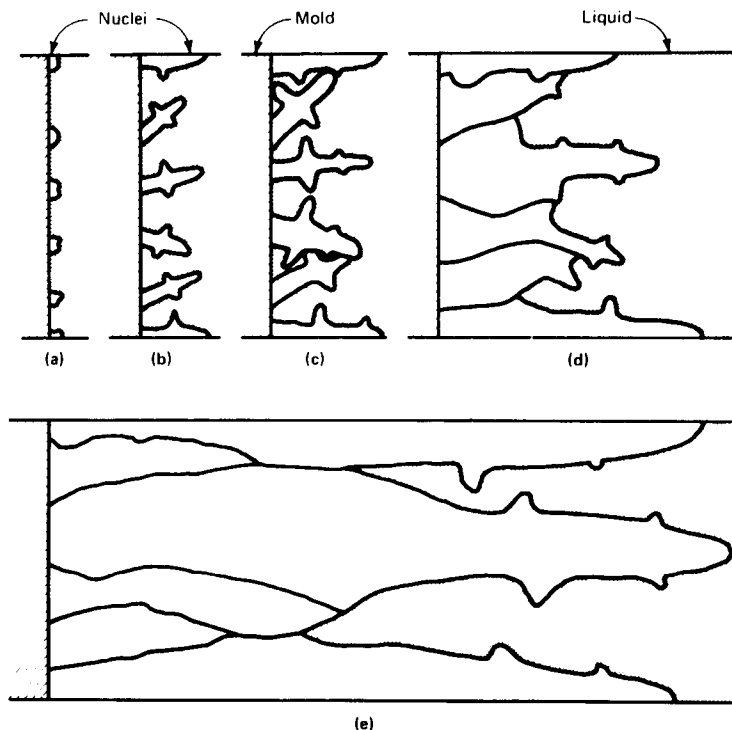
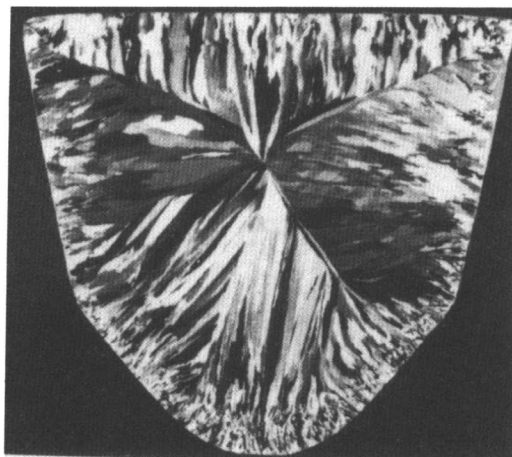


Fig. 2.5. Schematic illustration of the formation of columnar grains which have nucleated on a cold mold wall. (From Ref. 4, reproduced by permission of American Society for Metals.)

2.3 GROSS CHEMICAL SEGREGATION IN INGOTS

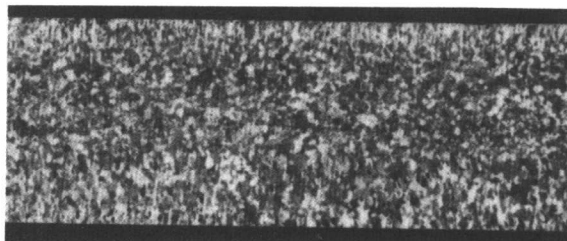
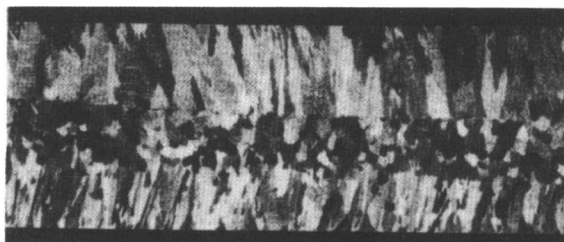
In the solidification of alloys, circumstances may permit gross segregation of solutes, so that there is a significant difference in the solute content on the outside of the ingot (which solidified first) and at the center of the ingot (which solidified last). The origin of this effect can be seen by referring to Fig. 2.8. For a binary alloy containing X_0 solute content, the first layer of a forming crystal has the composition X_1 . As the layer thickens, the composition increases, until, at steady stage growth, the solute content varies across the crystal and into the liquid as shown. Note that in the liquid just ahead of the solid there is a relatively high solute



Tucker's reagent

$1\frac{1}{2} \times$

Fig. 2.6. Microstructure of a transverse section through an ingot of commercially pure aluminum (1100 aluminum) cast by the wheel-and-belt method. Note that columnar grains have formed perpendicular to the mold wall, and also the small grains at the surface which were outgrown by the other grains. (Adapted from Ref. 7, reproduced by permission of American Society for Metals.)



Tucker's reagent

Actual size

Fig. 2.7. Effect of addition of a grain refiner on the cast grain size and shape of commercially pure aluminum (1100 aluminum) cast by a two-belt method. Both pictures are of longitudinal sections, shown at about actual sizes. The upper slab was cast without a grain refiner and the lower with a grain refiner addition, e.g. titanium or titanium and boron. (From Ref. 7, reproduced by permission of American Society for Metals.)

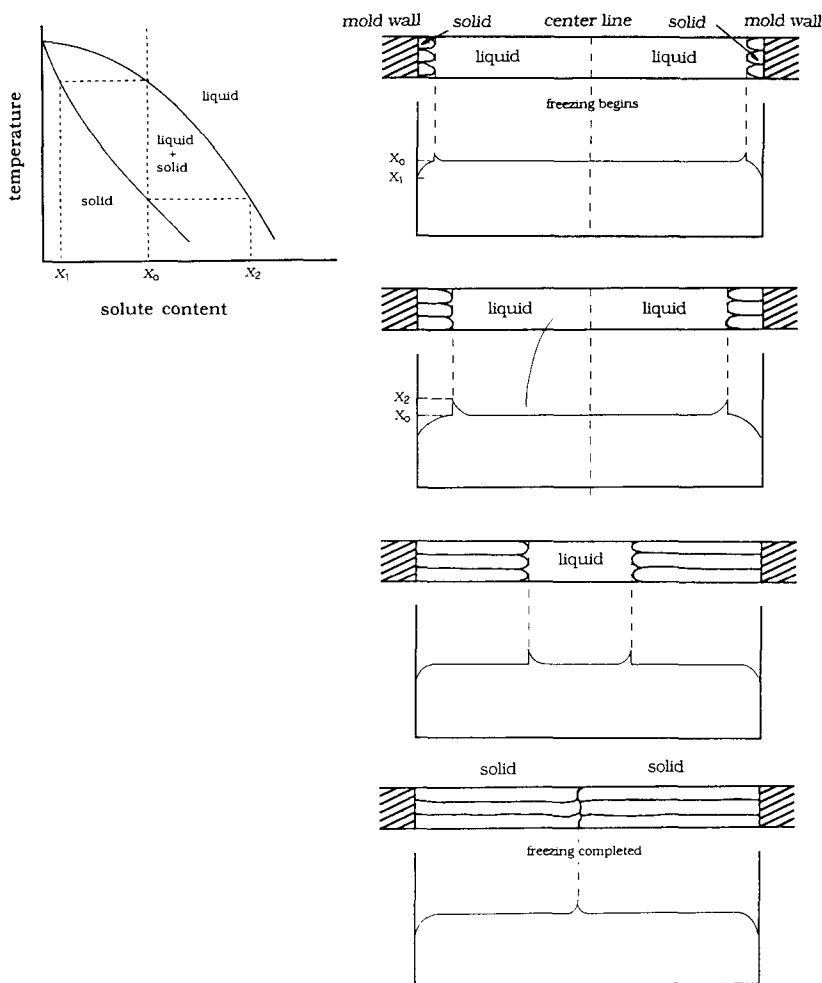


Fig. 2.8. Schematic illustration of the origin of gross ingot segregation.

content. When two crystals, each growing from opposite sides of the ingot, approach each other at the center line, the final liquid between these two crystals has a high solute content, and will freeze to form the solid of this solute content. (Note that this process is the same as used in zone refining.) This is a somewhat simplified description, and the degree and location of gross segregation in actual ingots depend upon the actual solidification process and the phase diagram.

2.4 DENDRITIC SEGREGATION (CORING)

In pure materials, the liquid freezes to a single crystalline phase of the same chemical composition as the parent liquid phase. In many alloys, the liquid freezes to a single crystalline phase of the same final composition as the parent liquid. However, the freezing process is usually complicated by two factors. One is that solidification occurs over a range of temperatures instead of at a discrete freezing temperature. The other is that the chemical composition of the first crystals to form is different from that of the parent liquid, but, as the temperature decreases and these grow, they must change their composition to that of the parent liquid by the completion of freezing.

To illustrate the process, equilibrium solidification will be examined first. A binary system of elements A and B is considered, with the phase diagram shown in Fig. 2.9.⁴ The alloy of interest contains 30 % B, and, upon cooling the liquid, freezing begins at temperature T_0 . The crystal has a composition of 10 % B. The formation of two nuclei is shown schematically in Fig. 2.10.⁴ (Here the distance between the two nuclei is

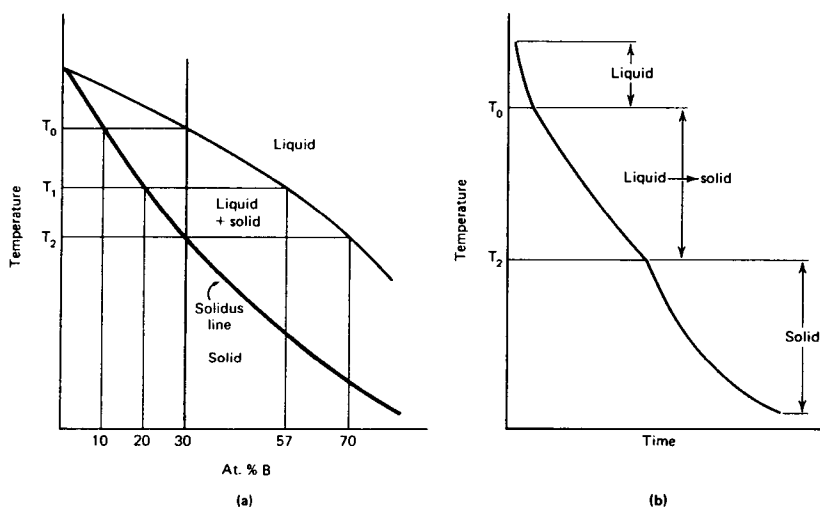


Fig. 2.9. Phase diagram for system A-B in which the liquid freezes to give a single crystalline phase by passing through a liquid-solid region. (From Ref. 4, reproduced by permission of American Society for Metals.)